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Results of Multi-Criteria Fire Detection System Tests

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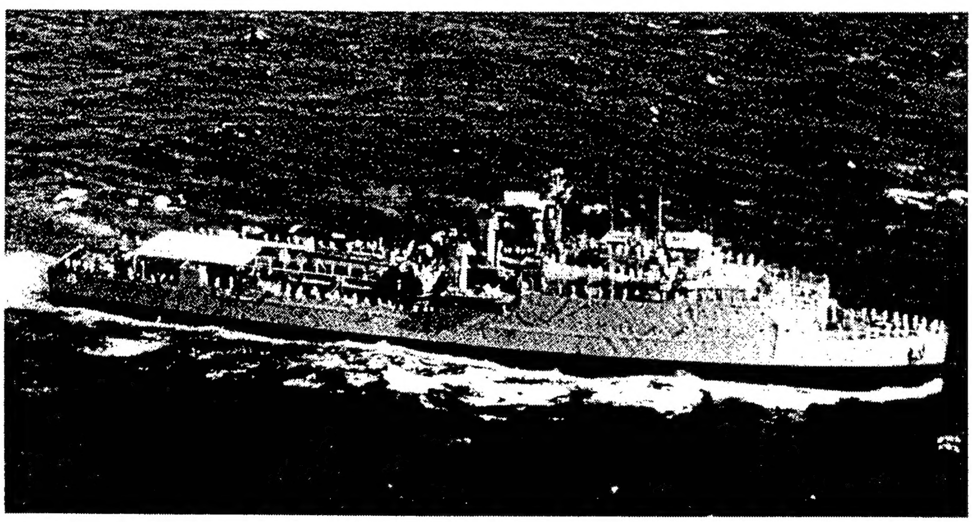

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13. ABSTRACT (*Maximum 200 words*)

A series of tests was conducted to evaluate and improve the multivariate data analysis methods and candidate sensor suites used for the Early Warning Fire Detection (EWFD) system under development. The EWFD system is to provide reliable warning of actual fire conditions in less time with fewer nuisance alarms than commercially available smoke detection systems. Tests were conducted from August 30 — September 3, 1999 onboard the ex-USS *Shadwell*. This report documents the test setup and results from the fire detector used during this test series.

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RESULTS OF MULTI-CRITERIA FIRE DETECTION SYSTEMS

1. INTRODUCTION

The first series of tests was conducted to evaluate an early warning fire detection system under development. The initial tests were conducted from August 30 - September 3, 1999 onboard the ex-USS SHADWELL, the Naval Research Laboratory's full scale fire research facility in Mobile, Alabama (reference (a)). The tests were used to evaluate and improve the multivariate data analysis methods and candidate sensor suites described in reference (b). This report documents the test setup and results from the fire detectors used during this test series. Results from the multivariant data analysis will be forthcoming.

2. BACKGROUND

The system under development combines a multi-criteria (sensor array) approach with sophisticated data analysis methods. Together an array of sensors and a multivariate classification algorithm can produce an early warning fire detection system with a low nuisance alarm rate. Several sensors measuring different parameters of the environment produce a pattern or response fingerprint for an event. Multivariate data analysis methods can be trained to recognize the pattern of an important event such as a fire. Multivariate classification methods, such as neural networks, rely on the comparison of fire events with nonevents i.e., background and nuisance sources. Variations in the response of sensors can be used to train an algorithm to recognize events when they occur. A key to the success of these methods is the appropriate design of sensor arrays and training sets of data used to develop the algorithm.

This test series included a variety of conditions that may be encountered in a real shipboard environment. Replicate measurements are important; therefore, several tests were repeated as closely as possible to provide replicates. Standard test conditions were established to facilitate comparisons amongst tests. The variations observed should be the components of the fire and not the way it was tested. It is unrealistic to test every possible fire or non-fire event that could occur in complex environments such as those found onboard ships, every effort was made to consider many representative situations and potential interference. For example, chemical sensors used in sensor arrays are seldom specific, so materials that are commonly found onboard ship were tested for response.

3. OBJECTIVES

The overall objective of this test series was to collect data from an array of candidate sensors exposed to real fire and nuisance sources in a shipboard environment (on the SHADWELL) to:

(1) Evaluate candidate sensor suites and probabilistic neural networks for early and reliable detection of several types of fires (i.e., develop a validation database);
(2) collect background and interference data;
(3) investigate the importance of smoke detector designs to the identification of

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fires/nuisance sources;

(4) obtain a database that will be used to improve the classifier for shipboard use (i.e., use the database as a secondary training set if the validation is not satisfactory); and

(5) assess the reliability of the multi-sensor detection system with respect to nuisance alarms.

4. APPROACH

To evaluate the ability of the candidate suites to detect and monitor a shipboard fire, the scenarios incorporated combustibles commonly found aboard a US Navy ship. The scenarios tested included flaming and smoldering Class A combustibles such as oily rags, paper, cardboard and cotton sheets. A standard heptane fire test was used to evaluate the sensor stability and influence of other changing parameters. Replicate tests also provided additional information that can be used to compensate for varying background conditions.

To test the reliability of the detection system with respect to alarm to nuisances, typical shipboard nuisance sources were tested. These included the use of personal care products, cleaning supplies and work related functions such as welding and cutting steel.

In addition, to provide an assessment of reliability and to reveal potential nuisance sources, a subset of the sensors were used to monitor daily activities onboard the SHADWELL after the test series. The arrays were moved to an area that allowed the sensors to be exposed to normal shipboard background conditions. The sensors monitored the CPO Mess and the Control Room. During this time, sensor responses were recorded and monitored. A dedicated person is logging all actions within the space.

5. EXPERIMENTAL TESTING

The detection system was installed in the forward area of the ship on the second deck in the compartment between Frames 15-22, port of the centerline beam. The compartment, detection system, selected SHADWELL sensors including thermocouples and continuous O_2, CO and CO_2 gas sampling locations are depicted in Figure 1. The SHADWELL sensors were used as secondary measurements to compare to the candidate detection sensors and to monitor the conditions of the compartment, in particular, temperature because the upper limit of the candidate detection sensors is 50°C (122°F). The standard test procedure exposed the sensors to 10 minutes of ambient air with the compartment buttoned up, followed by an exposure to a fire or nuisance alarm source for 20 minutes with all closures closed, and then data collected for 10 minutes while ventilating the compartment. Ventilation of the compartment consisted of opening the F stop, opening WTD 2-22-1, and turning the E1-15-2 fan on. Background tests were conducted by exposing the sensors to ambient conditions for the entire test period (40

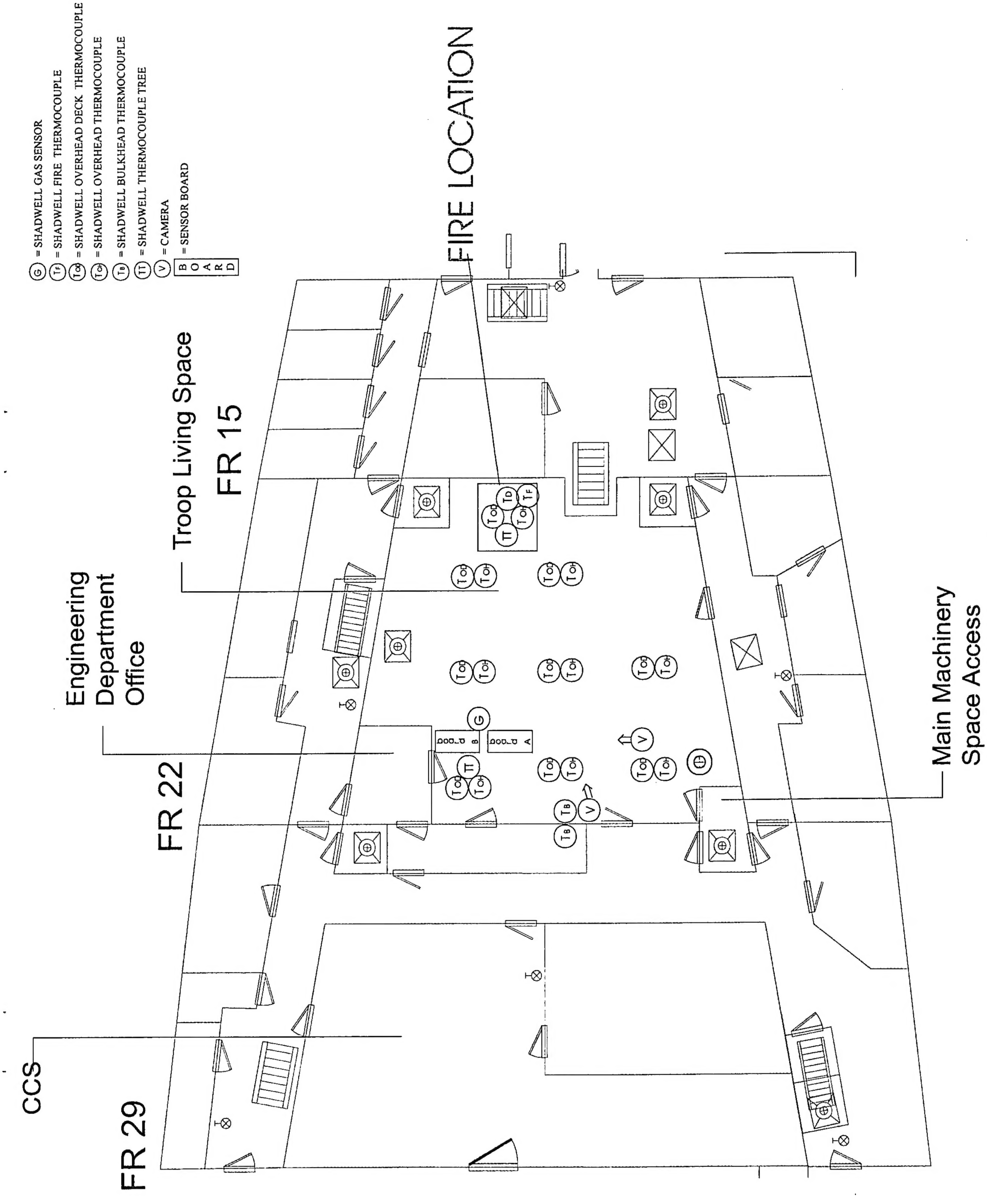

Figure 1 - Configuration of test area

minutes). After every 2 fire tests, a nuisance source test was conducted, so that the fire and nuisance tests were intermixed.

The sensors were calibrated with the appropriate gas at the upper concentration range of the specific sensor at the beginning of the test series. The sensors were checked daily with the calibration gases.

5.1 Test Area

The test area for this test series was between FR 15-22 on the second deck (Figure 1).

5.2 Fire Sources

A total of 18 fire tests was conducted to evaluate the detection system. Fire scenarios included common shipboard combustibles, such as oily rags, cardboard, paper, sheets and mattresses as the fuel. The fires were located in the forward section of the compartment (Figure 1). A summary of the fires is listed in Table 1.

Table 1 – Summary of Fire Sources

SCENARIO No.	FIRE SCENARIO	COMMENTS
1	Flaming Heptane in 11.4 cm (4.5 in.) diameter pan	Approximately 260 mL (8.8 fl oz) heptane in pan.
2	Flaming oily rags in a 6L (1.6 gal) metal trash can	3 - 0.1 m^2 (1ft^2) rags saturated with 118 ml (4oz) 10W30 motor oil, ignited with a butane lighter
3	Flaming paper and cardboard in a 6L (1.6 gal) metal trash can	5 Sheets of newspaper and 0.4 m^2 (4.5 ft^2) of cardboard rolled, ignited with a butane lighter
4	Smoldering oily rags in a 6L (1.6 gal) metal trash can	3 - 0.1 m^2 (1ft^2) rags saturated with 118 ml (4oz) 10W30 motor oil, 700 W calrod set at 50% used as a heat source
5	Smoldering paper and cardboard in a 6L (1.6 gal) metal trash can	5 Sheets of newspaper and 0.8 m^2 (9 ft^2) of cardboard rolled, ignited with a 700 W calrod set at 50%.
6	Smolder bedding material	2 sheets, wool blanket, cover, pillow, mattress and ticking. All were 6" square except for ticking which covered 2 sides of the mattress. Fuel package heated with a 700 W calrod set at 50%. Calrod laying on top-center of sample under its own weight.
7	Flaming fuel oil in 11.4 cm (4.5 in.) diameter pan	260 mL (8.8 fl oz) F-76 with 59 mL (2 fl oz) ethyl alcohol as an accelerant
8	Flaming wood crib	Crib constructed with 3 rows of 3 - 2.54 cm x 2.54 cm x 25.4cm (1 in. x 1 in. x 10 in.) sticks. Crib ignited with a small heptane pan fire.
9	Smoldering pillow in a pillow case, 15.2 cm x 15.2 cm (6 in. x 6 in.)	Fuel package heated with a 700 W calrod set at 50%. Calrod on top and center of sample under its own weight.
10	TODCO Wall Board exposed to a methanol flame	TODCO wallboard. 10 cm x 30 cm (4 in. x 1 ft). 846 ml (28.6 oz) methanol in a 11.43 cm (4.5 in.) diameter pan

SCENARIO No.	FIRE SCENARIO	COMMENTS
11	Pipe Insulation exposed to a methanol flame	Calcium silicate insulation with glass cloth lagging painted (45 cm, 17.7 in.). 846 ml (28.6 fl oz) methanol in a 11.43 cm (4.5 in.) diameter pan
12	Flaming bedding material	2 sheets, wool blanket, cover, pillow, mattress and ticking. All were 6" square except for ticking that covered 2 sides of the mattress. Fuel package was heated with a propane torch
13	Smoldering cable	LSDSGU-9 cable 2 conductor wire + ground (91.4 cm (36 in..) long) ohmically heated with a 300 A arc welder

5.2.1 Scenario 1 – Heptane Pool Fire

A small heptane pool fire was used periodically to determine the reproducibility and the stability of the sensors during the test series. Heptane is a typical hydrocarbon fuel used in standardized tests. Approximately, 260 ml (8.8 fl oz) of heptane in a 11.4 cm (4.5 in.) diameter pan was ignited with a torch. The pan was located 2.43 m (8 ft) below the overhead.

5.2.2 Scenario 2 – Flaming Oily Rags in Small Trashcan

A 6 L (1.6 gal) metal trashcan contained 3 pieces of 0.1 m^2 (1ft^2) cotton rags saturated with 118 ml (4 fl oz) of 10W30 motor oil. The rags were ignited with a butane lighter. The bottom of the trashcan was 2.43 m (8 ft) below the overhead.

5.2.3 Scenario 3 – Flaming Paper and Cardboard in Small Trashcan

Five whole sheets of newspaper and 1 sheet of 0.4 m^2 (4.5ft^2) cardboard were placed in a 6 L (1.6 gal) metal trash can. The newspapers were folded, slightly crumpled and then placed in the center of the cardboard that lined the trashcan. The newspapers were ignited with a butane lighter. The bottom of the trashcan was 2.43 m (8 ft) below the overhead.

5.2.4 Scenario 4 – Smoldering Oily Rags in Small Trashcan

Three pieces of 0.1 m^2 (1ft^2) cotton rags saturated with 118 ml (4 fl oz) of 10W30 motor oil were placed in a 6 L (1.6 gal) metal trash can. A 2.54 cm (1 in.) diameter hole, 2.54 cm (1 in.) above the bottom of the trashcan, was drilled into the trashcan. A 14.7 cm (5.5 in.) calrod (Ogden Model MWEJ05J1870) was inserted into the hole of the trashcan. 12.7 cm (5 in.) of the calrod was allowed to rest on the rags. The 700 W calrod was energized via a variac to 50% of capacity. The bottom of the trashcan was 2.43 m (8 ft below the overhead).

5.2.5 Scenario 5 – Smoldering Paper and Cardboard in Small Trashcan

Five whole sheets of newspaper and 2 sheets of 0.4 m^2 (4.5 ft^2) cardboard were placed in a 6L (1.6 gal) metal trash can. The newspapers were folded, slightly crumpled and then placed in the center of the cardboard that lined the trashcan. A 14.0 cm (5.5 in.) calrod was inserted in the 2.54 cm (1 in.) hole of the same trashcan used in scenario 4. Some of the newspaper was in

contact with the calrod. The bottom of the trashcan was 2.43 m (8 ft) below the overhead.

5.2.6 Scenario 6 – Smoldering Bedding Material

A Navy mattress (MIL-M-18351F(SH)) consisting of a 11.4 cm (4.5 in.) thick Safeguard polychloroprene foam core covered with a fire retardant cotton ticking was outfitted with the following items:

1) Two sheets - Federal Specification DDD-S-281,
2) One blanket - Federal Specification MIL-B-844, and
3) One bed spread - Federal Specification DDD-B-151.

The composite fuel source was cut into 15 cm x 15 cm (6 in. x 6 in.) squares.

The smoldering fire source consisted of placing one square sample 1.5 m (5 ft) below the ceiling with a 700 W calrod resting on the center of the top blanket. The calrod was energized with a variac to 50% of capacity. The bedding materials were laid flat on top of the mattress sample in the above order. The calrod was allowed to rest on the sample under its own weight. The power to the calrod was turned on after the initial background data were collected, and remained on throughout the test.

5.2.7 Scenario 7 – F-76 Fuel Oil Pool Fire

A pool fire was produced by burning 260 ml (8.8 fl oz) of F-76 fuel oil in an 11.4 cm (4.5 in.) diameter pan. Approximately, 59 ml (2 fl oz) of ethyl alcohol were used as an accelerant. A torch was used to ignite the pan that was located 2.43 m (8 ft) below the overhead.

5.2.8 Scenario 8 – Wood Crib Fire

A small wood crib constructed with three rows of three wood sticks (2.54 cm x 2.54 cm x 25 cm (1 in. x 1 in. x 10 in.)) was ignited with a small heptane pool fire. A 15.24 cm (6 in.) diameter pan containing 115 ml (3.9 oz) heptane was placed underneath the wood crib. The heptane pan was ignited with a torch. After the crib ignited, the heptane pan was removed from under the crib. A smoke blanket was used to extinguish the heptane fire. The bottom of the wood crib was located 2.43 m (8 ft) below the overhead.

5.2.9 Scenario 9 – Smoldering Pillow in a Pillowcase

A Navy feather pillow (Federal Specification V-P-356, Type 4) and a pillowcase (Federal Specification DDD-P-351) were cut and stapled into a 15 cm x 30 cm (6 in. x 12 in.) sample. The sample was ignited 1.5 m (5 ft) below the ceiling by placing a calrod on the top center of the sample under its own weight. The power to the 700 W calrod via a variac set on 50% was turned on after the background data were collected.

5.2.10 Scenario 10 – Nomex Honeycomb Wall Board

The white, TODCO Engineering Products, Nomex panel used in this test was a non-filled honeycomb with phenolic resin impregnated fiberglass facing over the aramid fiber honeycomb core. The honeycomb was 0.6 cm (0.25 in.) hexagonal MIL SPEC MIL-C-81986, with a density of 48 kg/m^3 (3 lb/ft^3). The overall panel thickness was 1.6 cm (- 0.08 cm, +0.000 cm) (0.625 in. ((-0.030 in., +0.000 in.)) thick including the decorative face sheets. The decorative face sheets were high pressure laminate (HPPL) in accordance with MIL SPEC MIL-P-17171, Type IV except that they were 0.07 cm to 0.09 cm (0.027 in. to 0.037 in.) thick. The HPPL was bonded directly to the fiberglass face sheet using the phenolic resin system per MIL SPEC MIL-R-9299, Grade A.

The sample 30 cm (12 in.) high and 10 cm (4 in.) wide was exposed to a methanol flame from an 11.43 cm (4.5 in.) diameter fuel pan. The fuel pan contained 846 ml (28.6 oz) of methanol. The wallboard was mounted at a 60° angle to the flame source. The wallboard and flame source were on a platform 1.5 m (5 ft) below the overhead.

5.2.11 Scenario 11 – Pipe Insulation Exposed to a Flame

Calcium silicate insulation with glass cloth lagging pipe insulation was exposed to a methanol flame. The insulation was obtained from Reilly Benton Insulation Co., a Navy supplier. The calcium silicate sample (MIL-I-278) was 5.1 cm (2 in.) internal pipe size and 2.54 cm (1 in.) thick. The glass lagging cloth (MIL-C-20075, Ty CL 3, Reilly Benton Type 300) was applied to the calcium silicate with MIL-A-3316 Class I Grade A adhesive (Vimasco 713).

The insulation was cut in 45 cm (18 in.) long samples and mounted in a 60° angle around PVC pipe with corresponding diameters. The lagging was then applied around the insulation per manufacturer's instruction. After assembly, samples were painted with chlorinated Alkyd White, DOD-E-24607, Color 27880.

The insulation and pipe assembly was exposed to a methanol flame from 11.43 cm (4.5 in) diameter fuel pan. The fuel pan contained 846 ml (28.6 oz) of methanol. The assembly was mounted at a 60° angle to the flame source. The sample and flame source were on a platform 1.5 m (5 ft) below the overhead.

5.2.12 Scenario 12 – Flaming Bedding Material

A Navy mattress (MIL-M-18351F(SH)) consisting of a 11.4 cm (4.5 in.) thick Safeguard polychloroprene foam core covered with a fire retardant cotton ticking was outfitted with the following items:

1. Two sheets - Federal Specification DDD-S-281,
2. One blanket - Federal Specification MIL-B-844, and
3. One bed spread - Federal Specification DDD-B-151.

The composite fuel source was cut into 15 cm x 15 cm (6 in. x 6 in.) squares. A propane torch was used as the ignition source. The flame was concentrated on the center top surface of the bedding. The sample and flame source were on a platform 1.5 m (5 ft) below the ceiling. The bedding did not sustain flaming combustion.

5.2.13 Scenario 13 – Smoldering Electrical Cable

A 91.4 cm (36 in.) section of LSTSGU-9[a] cable was energized with a 300 amp POWERCON arc welder. The wires have radiation crosslinked polyolefin jackets with silicon rubber insulation that is considered a low smoke cable material. The jacket and insulation were stripped back on both ends exposing 1.25 cm (0.5 in.) of both of the conductors. The arc welder was clamped to both conductors on one end of the cable and the other end was grounded to a metal stand. After initial background data were collected, the arc welder was energized to 300 amps. The cable remained energized until the end of the test.

5.3 Nuisance Sources

A total of 7 nuisance source scenarios were developed to represent shipboard activities, including welding, cutting steel with a torch, toasting bread, smoking, cleaning, the use of personal care products and burning popcorn. The sources were intended to yield smoke detector alarms or a significant response from the gas sensors. Table 2 summarizes the nuisance sources.

Table 2 – List of Nuisance Source Scenarios

SCENARIO No.	NUISANCE SCENARIO	COMMENTS
1	Burning Toast	4 slices of white bread in a four-slice toaster. Toaster set to dark and lever clamped down for 7 min.
2	Burning popcorn in microwave	Cook popcorn on high for 12 minutes
3	Welding	Arc welding of a 0.48 cm (0.18 in.) thick steel plate. Used 0.32 cm (0.125 in.) #7018 rods. Arc welder set on 100 amps
4	Cutting steel with acetylene torch	0.48 cm (0.18 in.) thick steel plate cut with oxy-acetylene torch. Steel plate had a coat of green primer.
5	Cleaning supplies (Simple Green, Pine Sol, All Purpose Cleaning Packs, Lysol Aerosol Disinfectant	Vapor from typical cleaning supplies
6	Cigarette/ cigar smoke	Chain smoking. 10 cigarettes and one cigar
7	Personal care products such as rubbing alcohol, Ben-Gay, shaving cream, and Tinactin	Vapor from typical personal care products

[a] Cable manufactured by Monroe Cable Co, Military Part No. Mil C-24643/15-03UN, 9AWG, 2 conductor.

5.3.1 Scenario 1 - Burning Toast

Four slices of white bread were placed in a four-slice toaster (Toastmaster Model D165, 120 V, 50-60 Hz, 1700 W) located 1.5 m (5 ft) below the ceiling. The toaster lever was set to "dark," and the lever was clamped down to allow continual heating and burning of the toast. The toaster was unplugged when flaming occurred. This event represented a cooking event that can occur in a pantry or galley. Cooking events have not been identified as a large source for nuisance alarms onboard ship. However, there is little documented information characterizing shipboard detection systems performance. The inclusion of several cooking events was deemed appropriate since cooking events are the leading causes of nuisance alarms with residential detectors, which work on the same principles of operation as conventional smoke detectors onboard ships.

5.3.2 Scenario 2 - Burning Popcorn in Microwave

Burning popcorn in a microwave is a plausible event that may occur in a pantry. This source consisted of heating a standard popcorn pack in a Tappan Model TMT1046150, 120 V, 11.4 A, 60 Hz, 850 W microwave oven set to high for 12 minutes. The microwave was on a platform 1.5 m (5 ft) below the ceiling.

5.3.3 Scenario 3 - Welding

Welding and other hot work are typical maintenance activities that can occur onboard a ship. Welding of steel was conducted in the compartment 2.4 m (8 ft) below the ceiling. The arc welding consisted of running a weld across a 0.48 cm (0.189 in.) thick steel plate using a 0.32 cm (0.125 in.) number 7018 rod and a constant current setting of 100 A. A total of 14 rods was used during the 20 minute period.

5.3.4 Scenario 4 - Cutting Steel with Acetylene Torch

An oxy-acetylene torch was used to cut a 0.48 cm (0.189 in.) thick steel plate, 2.4 m (8 ft) below the ceiling. Cutting occurred in a continuous fashion by cutting off 30 cm (12 in.) long strips of steel from the plate. A total of 21 strips were cut in the 20 minutes.

5.3.5 Scenario 5 – Cleaning with Cleaning Agents

Two people positioned 1.5 m (5 ft) under the sensor boards used various cleaning products. The cleaning products and respective ingredients are listed below and are typical agents that may be used on a ship. The two people cleaned a 91.44 cm x 114.3 cm (36 in. x 45 in.) steel plate and a 53.3 cm (21 in.) diameter, 50.8 cm (20 in.) deep kettle. The cleaning products were used generously as if in actual cleaning.

- Simple Green
  - Water, surfactants, wetting agents, chelating agent, fragrance colorant, 2-butoxyethanol, ethylene glycol monobutyl ether (EGBE) and ethylene glygol monobutyl ether acetate (EGBEA)

monobutyl ether acetate (EGBEA)

- All Purpose Cleaning Pack in 1.5 gal water
  - Sodium carbonate, citric acid, anionic and non ionic surfactants

- Lysol Aerosol Disinfectant
  - Alkyl (50% C_{14}, 40% C_{12}, 10% C_{16}), dimethyl benzyl ammonium saccharinate (0.1%), ethanol (79.0%), inert ingredients (20.9%)

- Pine Sol
  - Pine oil (15%), inert ingredients (85%)

5.3.6 Scenario 6 – Cigarette/Cigar Smoke

Although smoking is prohibited inside Navy ships, it still remains a very plausible nuisance source. The cigarette smoke test consisted of chain smoking cigarettes (Parliament Lights and Salem Menthol) and one Swisher Sweet cigar within the compartment. A total of 10 cigarettes and 1 cigar was smoked in the 20 minute test period.

5.3.7 Scenario 7 – Personal Care Products

Three people were positioned under the sensor boards and liberally used typical personal care products that may be brought onboard a ship. The products and ingredients are listed below:

- Rubbing Alcohol
  - 70% Isopropyl

- Tinactin Antifungal – Liquid Aerosol
  - Tolnafta, alcohol SD-40-2 (36%), BHT, PPG-12 Buteth-16

- Edge Gel Shaving Cream with Aloe
  - Deionized water, palmitic acid, triethanolamine, pentane, fatty acid esters, palimitamine oxide, lauryl alcohol, aloe, isobutane

- Ben Gay – Ultra Strength
  - Methyl salicylate 30%, methanol 10%, camphor 4%

5.4 Detection System

The sensors were organized into two sensor arrays and each were mounted on a board 1 m x 0.5 m (3.3 ft x 1.6 ft). The two sensor arrays were mounted side by side to the underside of the FR 20 and FR21 overhead beams (0.3 m (1 ft) below the overhead). The layout of the two sensor arrays is depicted in Figures 2, 3, and 4. Table 3 presents a list of the instruments that were used in the tests. Under the column labeled species, the parenthetical term represents the sensor name used throughout this program.

5.4.1 Gas Sensors

The majority of the gas sensors were electrochemical cell technology made by City Technology. These sensors were used because they provided a means to economically measure many species. Past experience with the carbon monoxide (CO) sensors indicated that these sensors are accurate at low ppm concentrations, are easy to operate and calibrate and are reliable over repetitive testing. The general hydrocarbon sensor is a solid state metal oxide sensor. The carbon dioxide (CO_2) meter was designed for indoor air quality measurements based on non-dispersive infrared (NDIR) technology. All of the gas sensors operated via gas diffusion.

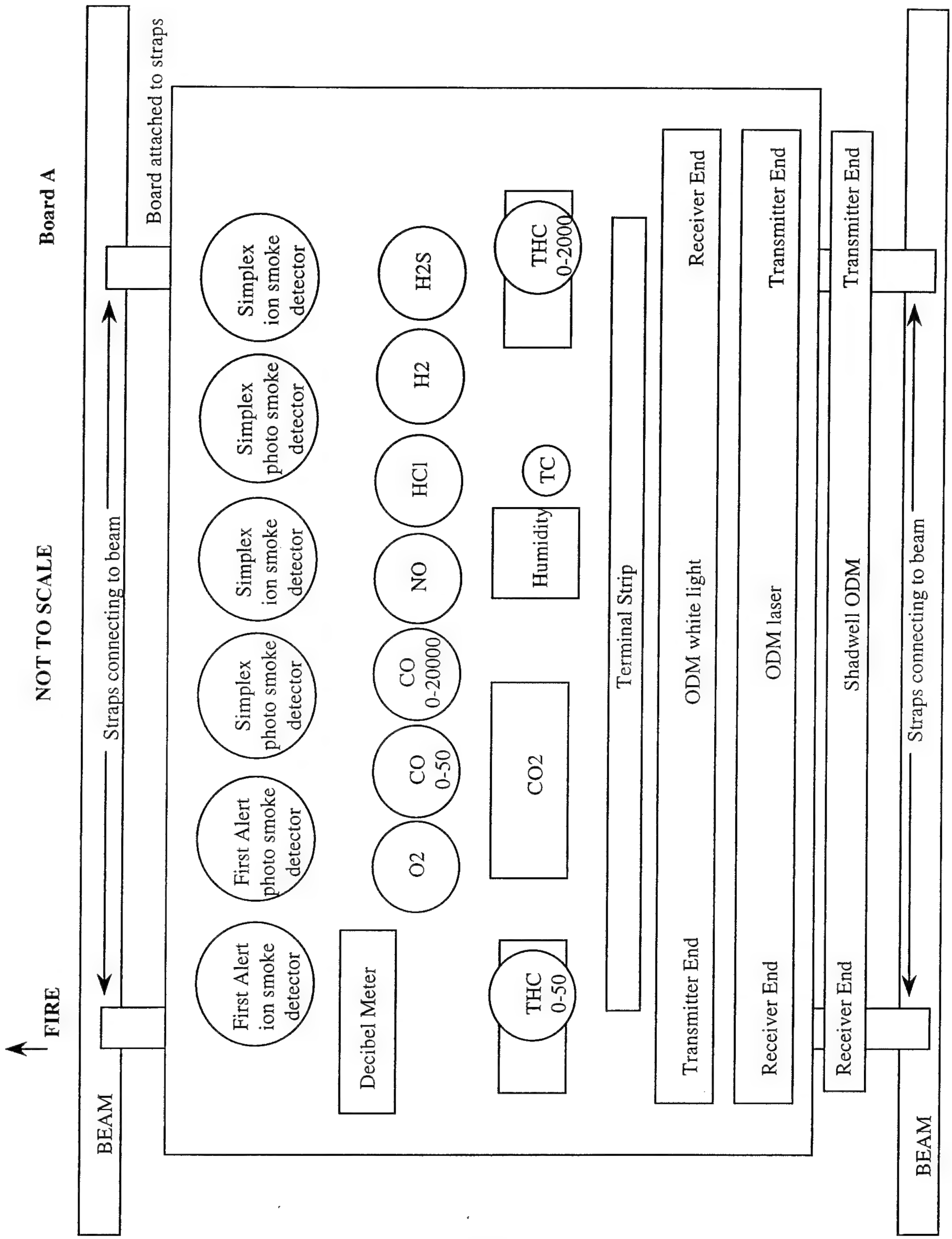

Figure 2 – Layout of sensors on Board A as mounted on the beam, looking up from starboard to port.

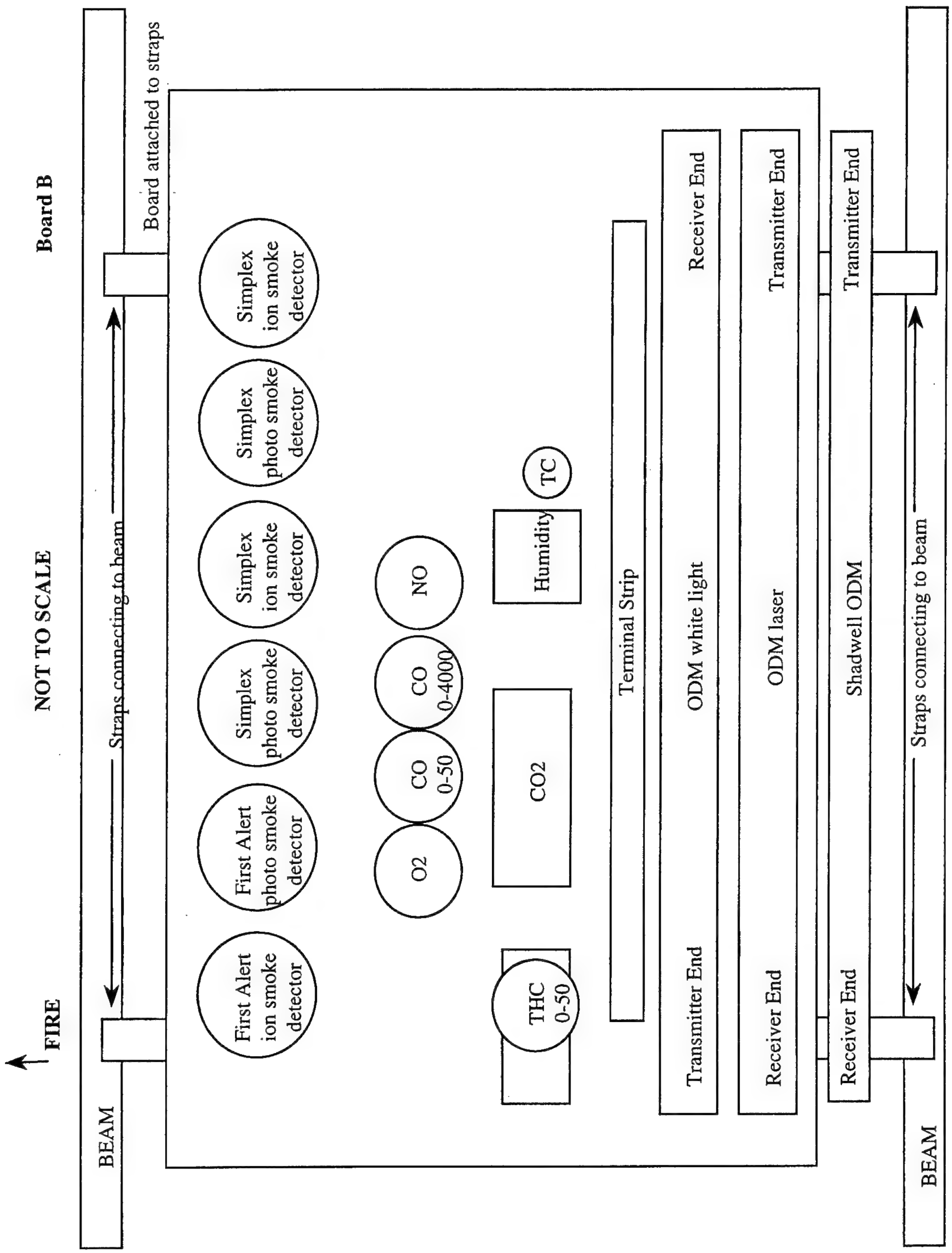

Figure 3 - Layout of sensors on Board B as mounted on the beam, looking up from starboard to port.

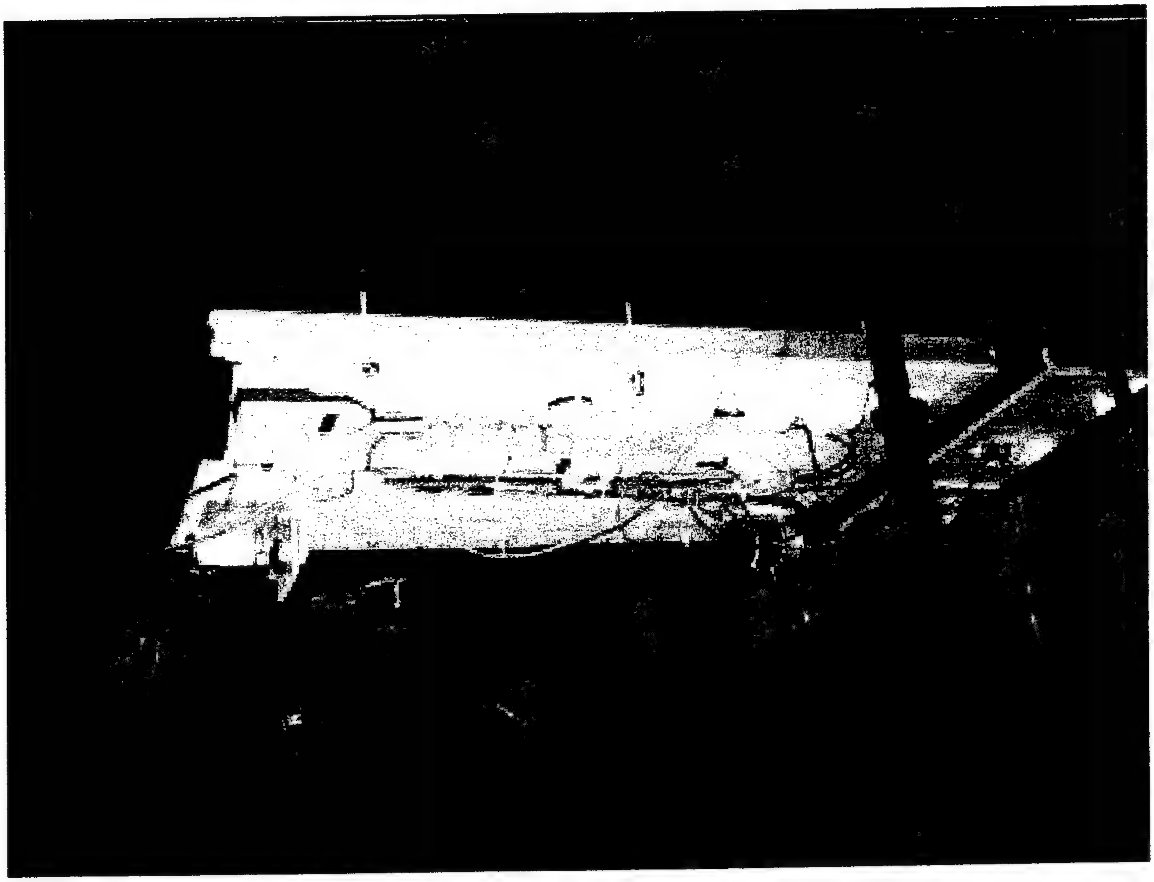

Figure 4 – Photograph of sensor Board A mounted in the overhead, looking aft.

Table 3. Instrumentation for Multi-criteria Detection Tests

No.	Species	Sensor Range	Resolution	Instrument Model No.	Manufacturer
1	Oxygen (O_2)	0-25%	0.1% O_2	6C	City Technology
2	Carbon monoxide w/ H_2 compensation ($CO_{4000\ ppm}$)	0-4000 ppm	1 ppm	A3ME/F	City Technology
3	Carbon monoxide ($CO_{50\ ppm}$)	0-50 ppm	0.5 ppm	TB7E-1A	City Technology
4	Carbon dioxide (CO_2)	0-5000 ppm	Accuracy= greater of $\pm$5% of reading or $\pm$100 ppm	2001V	Telaire/Englehard
5	C_1 to C_6 Hydrocarbons (calibrated with ethylene)	0-50 ppm	$\pm$2.5 ppm	SM95-S2	International Sensor Technology
6	C_1 to C_6 Hydrocarbons (calibrated with ethylene)	0-2000 ppm			International Sensor Technology
7	Hydrogen (H_2)	0-200 ppm	2 ppm	TE1A-1A	City Technology
8	Nitric oxide (NO)	0-20 ppm	0.5 ppm	TF3C-1A	City Technology
9	Hydrogen chloride (HCl)	0-10 ppm	0.5 ppm	TL1B-1A	City Technology
10	Hydrogen sulfide (H_2S)	0-5 ppm	0.1 ppm	TC4A-1A	City Technology
11	Temperature (Thermocouple or TC)	-200 to 1250EC	1EC or 0.75%	Type K, 0.127 mm bare bead TC	Omega
12	Temperature (Temp Omega)	-20EC to 75EC	$\pm$0.6EC accuracy	HX93 transmitter (RTD)	Omega
13	Relative humidity (RH)	3-95%	$\pm$2% RH accuracy	HX93 transmitter	Omega
14	Photoelectric smoke detector (Photo)	0 - 19% Obs/m		4098-9701	Simplex
15	Ionization smoke detector (ION)	1.6 -10% Obs/m		4098-9716	Simplex
16	Residential ionization smoke detector (RION)			83R	First Alert
17	Residential photoelectric smoke detector (Photo)			SA203B	First Alert
18	White Light Optical Density Meter (1 m path length)			Type 4515 spot white light, 2.4 V Weston 856-RR Photovoltaic Cell	Grainger Huygen Corp.
19	670 nm Laser Optical Density Meter (1 m path length)			VDM-2 670 nm, 2 mW laser MRD 500 PIN silicon Photodiode	Meredith Motorola
20	880 nm Laser Optical Density Meter (1 m path length)			Laser and photodiode	TSI

5.4.2 Smoke Detectors

Multiple technologies and devices were used to obtain smoke measurements. The benchmark measurements of performance consisted of conventional, commercial photoelectric and ionization smoke detectors, currently installed onboard ship. The Simplex ionization detectors (Model 4098-9717) and the Simplex photoelectric detectors (Model 4098-9714) were monitored with a single alarm panel (Simplex Model 4020). This fire alarm system provided time of alarm for the exposed detectors. The alarm verification feature was enabled for these detectors so that performance could be evaluated based on the goal of minimizing nuisance alarms. The alarm sensitivity of these detectors was set to 8% obscuration/m (2.5% obscuration /ft) for photoelectric and 4.2% obscuration /m (1.3% obscuration /ft) for ionization. Additional Simplex detectors were also used with a specially designed hardware/software package which polled the detectors every 4 to 5 seconds and saved the data to a computer file. Based on experimental data, the detector outputs can be correlated to percent obscuration measurements. In addition to the commercial smoke detectors, a residential ionization smoke detector (First Alert 83R) and a residential photoelectric smoke detector (First Alert SA203B) were also included. The residential ionization detector is a standard battery operated single station unit that was modified to provide an analog voltage output to the MASSCOMP, the data acquisition system. Although a direct correlation to percent obscuration was not available from the residential ionization detector, the signal provided a secondary means of measuring the change in smoke density. The residential photoelectric detector provided an audible alarm that was recorded with a decibel meter. Test participants in the compartment also relayed to the control room when the detectors went into alarm.

5.4.3 Optical Density

Three different instruments were used to measure smoke optical density. Multiple measurements were used to assess the impact of varying designs on the usefulness of the smoke signature in the PNN alarm algorithm. The previous work (reference (b)) indicated that sensor design may be a significant factor in the effectiveness of the PNN to distinguish between real fires and nuisance alarm sources. The laser (670 nm)/photodiode optical density meter (ODM) used in the previous work was used in these experiments. A white light ODM also used in part of the previous study was included. The white light ODM consisted of a spot light and a photocell consistent with the specifications in UL 217, Standard for Single and Multiple Station Smoke Alarms. The third ODM was the standard TSI smoke meters utilized on the SHADWELL (reference (c)). The TSI smoke meters have a 1 m path length and a light source with a peak wavelength of 880 nm. All ODMs were setup with 1m pathlengths. The calibration of the smoke meters was checked each morning. Prior to installation, the smoke meters were calibrated using neutral density filters. The computer output for the TSI smoke meters was percent transmittance.

5.5 Video Cameras

Two video cameras were installed to observe and record the fire/activity and also the smoke movement in the test compartment. The location of the cameras is depicted in Figure 1.

5.5 Test Procedures

At the beginning of each day, the daily checklist was completed (Appendix A). Prior to each test, the test area was cleared of all personnel not involved with testing from the main to the third deck and from frames 29 forward. All hatches and doors were closed. Ventilation to the space remained off. Closures remained the same for the first 30 minutes of the test. After completion of these tasks, test personnel were positioned in the appropriate locations. When the fuel package was prepared and the safety team in position, data collection and videos were initiated. Following approximately 10 minutes of background data, either the fire was ignited, the "nuisance activity" initiated or for the smoldering fire scenarios, the calrod energized. During the test, SHADWELL personnel made visual observations. Event data were collected for 20 minutes. After the 20 minutes, the compartment was ventilated by opening the "f-stop" at 2-15-1 and WTD 2-29-1 and turning on the E1-15-1 fan. Data collection continued for 10 additional minutes to assess the recovery of the sensors following an event. Once the Safety Team deemed the test area safe for personnel without breathing protection, the area was prepared for the next test. This preparation included cleanup of the test area, equipment setup for the next test and verification of instruments.

6. RESULTS AND DISCUSSION

Table 4 lists all the tests that were performed in this test series. The following describes the information in each column of Table 4. Timelines for all the tests are located in Appendix B.

Column 1	Test name
Column 2	Date the test was performed
Column 3	Description of the test
Column 4	Comments
Column 5	Outside air temperature
Column 6	Relative humidity of the outside air
Column 7	Wind speed in mph
Column 8	Wind direction in degrees
Column 9	Masscomp start time
Column 10	Fire source ignition time or the time when the source was energized.
Column 11	Fuel package flame time (i.e., the time that flaming ignition occurred).
Column 12	Fire extinguished time
Column 13	Ventilation initiation time
Column 14	Masscomp secure time

6.1 Electrochemical Sensors Stability

Four heptane tests were performed during this test series to evaluate the stability of the sensors. During the first two heptane tests, MV_01 and MV_02, it was determined that RF transmissions from the hand held radios interfered with the electrochemical sensors. Communications during subsequent tests were performed with sound powered phones, which did not cause any signal noise on sensor outputs. For this analysis, the data were filtered. During the last heptane test, MV_21, the upper compartment temperatures exceeded the upper limit of the electrochemical sensors; therefore, the test was terminated before completion of the 20 minute burn period.

Table 4 - Summary of tests

Test Name	Date	FIRE SCENARIO	COMMENTS	Ambient Conditions				Time Data					
				Temp (°F)	Rel. Humidity (%)	Wind Speed (mph)	Wind Direction (degrees)	Start Data Acquisition	Source Initiated minutes	Fire Ignition minutes	Fire Extinguished minutes	Ventilate minutes	Halt Data Collection minutes
MV_00	8/30/99	Background	10 + 20 minutes buttoned up, 10 minutes ventilation. 40 minutes total time	86	78	14	140	13:52:12				34.83	44.32
MV_01	8/30/99	Flaming Heptane in 11.4 cm (4.5 in) diameter pan	Approximately 260 mL (8.8 fl oz) heptane in pan.	85	80	13	170	14:47:03	12.15		32.08	32.75	42.77
MV_02	8/30/99	Flaming Heptane in 11.4 cm (4.5 in) diameter pan	Approximately 260 mL (8.8 fl. oz.) heptane in pan.	82	84	25	29	17:25:46	10.63		29.02	29.98	40.12
MV_03	8/31/99	Background	10 + 20 minutes buttoned up, 10 minutes ventilation. 40 minutes total time	77	85	14	62	10:50:44				26.50	37.03
MV_04	8/31/99	Flaming Heptane in 11.4 cm (4.5 in) diameter pan	Approximately 260 mL (8.8 fl oz) heptane in pan.	84	74	9	74	11:44:35	11.47		31.35	31.90	42.65
MV_05	8/31/99	Flaming oily rags in a 6L (1.6 gal) metal trash can	3 - 0.1 m^2 (1 ft^2) rags saturated with 118 ml (4oz) 10W30 motor oil, ignited with a butane lighter	84	75	17	81	12:53:56	10.28		25.58	26.63	36.62
MV_06	8/31/99	Burning Toast	4 slices of white bread in a four-slice toaster. Toaster set to dark and lever clamped down for 7 min.	85	77	19	75	14:22:23	10.50			25.98	36.13
MV_07	8/31/99	Flaming paper and cardboard in a 6L (1.6 gal) metal trash can	5 Sheets of newspaper and 0.4 m^2 (4.5 ft^2) of cardboard rolled, ignited with a butane lighter	85	76	18	74	15:36:56	10.32	10.42	14.63	30.75	40.83
MV_08	8/31/99	Smoldering oily rags in a 6L (1.6 gal) metal trash can	3 - 0.1 m^2 (1 ft^2) rags saturated with 118 ml (4oz) 10W30 motor oil, 700 W calrod set at 50% used as a heat source	85	73	16	76	16:41:07	10.27			46.12	56.38
MV_09	8/31/99	Burning popcorn	Cook popcorn on high for 12 minutes	84	77	21	83	17:55:12	10.05			24.15	34.33
MV_10	9/1/99	Flaming oily rags in a 6L (1.6 gal) metal trash can (repeat of MV_05)	3 - 0.1 m^2 (1 ft^2) rags saturated with 118 ml (4oz) 10W30 motor oil, ignited with a butane lighter	76	78	12	25	9:12:30	10.12		18.88	19.42	29.85
MV_11	9/1/99	Flaming paper and cardboard in a 6L (1.6 gal) metal trash can	5 Sheets of newspaper and 0.8 m^2 (9 ft^2) of cardboard rolled, ignited with a butane lighter	75	81	12	32	9:52:55	10.13	15.00		30.50	40.55

Table 4 - Summary of tests

Test Name	Date	FIRE SCENARIO	COMMENTS	Ambient Conditions				Time Data					
				Temp (°F)	Rel. Humidity (%)	Wind Speed (mph)	Wind Direction (degrees)	Start Data Acquisition	Source Initiated minutes	Fire Ignition minutes	Fire Extinguished minutes	Ventilate minutes	Halt Data Collection minutes
MV_12	9/1/99	Welding	Arc welding of a 0.48 cm (0.18 in) thick steel plate. Used 0.32 cm (0.125 in) #7018 rods. Arc welder set on 100 amps	76	80	8	36	11:20:13	10.10			30.70	40.95
MV_13	9/1/99	Background	10 + 20 minutes buttoned up, 10 minutes ventilation. 40 minutes total time	81	70	5	58	12:19:09				31.18	40.50
MV_14	9/1/99	Smoldering paper and cardboard in a 6L (1.6 gal) metal trash can	5 Sheets of newspaper and 0.8 m^2 (9 ft^2) of cardboard rolled, ignited with a 700 W calrod set at 50%.	81	72	10	50	13:13:37	10.17		31.45	32.02	42.28
MV_15	9/1/99	Smolder bedding material	2 sheets, wool blanket, cover, pillow, mattress and ticking. All were 6" square except for ticking which covered 2 sides of the mattress. Fuel package heated with a 700 W calrod set at 50%. Calrod on top and center of sample under its own weight.	81	72	12	26	14:16:39	10.13		30.73	31.25	41.45
MV_16	9/1/99	Cutting steel with acetylene torch	0.48 cm (0.18 in) thick steel platecut with oxy-acetylene torch. Steel plate had a coat of green primer.	82	72	7	43	16:14:55	10.78		31.50	31.97	42.35
MV_17	9/1/99	Flaming fuel oil in 11.4 cm (4.5 in) diameter pan	260 mL (8.8 fl oz) F-76 with ethyl alcohol accelerant	82	73	3	67	17:33:39	10.93	10.93	22.15	22.65	
MV_18	9/2/99	Flaming wood crib	Crib constructed with 3 rows of 3 - 2.54 cm x 2.54 cm x 25.4cm 1 in x 1 in x 10 in) sticks. Crib ignited with a small heptane pan fire.	75	100	3	60	8:53:07	10.53	10.53	18.33	18.82	30.18
MV_19	9/2/99	Cleaning supplies (Simple Green, Pine Sol, All Purpose Cleaning Packs, Lysol Aerolsol Disinfectant	Vapor from typical cleaning supplies	75	100	7	39	9:55:58	10.03			26.20	36.27
MV_20	9/2/99	Smoldering pillow in a pillow case, 15.2 cm x 15.2 cm (6 in x 6 in)	Fuel package heated with a 700 W calrod set at 50%. Calrod on top and center of sample under its own weight.	77	97	6	45	11:02:17	10.10	10.10	37.57	38.00	48.12
MV_21	9/2/99	Flaming Heptane in 11.4 cm (4.5 in) diameter pan	Approximately 260 mL (8.8 fl oz) heptane in pan.	78	95	8	79	12:01:21	11.12		26.92	27.50	38.05
MV_22	9/2/99	Cigarette/ cigar smoke	4 people chain smoking. 10 cigarettes and one cigar	79	90	7	68	13:26:52	10.17			20.88	30.85

Table 4 - Summary of tests

Test Name	Date	FIRE SCENARIO	COMMENTS	Ambient Conditions				Time Data					
				Temp (°F)	Rel. Humidity (%)	Wind Speed (mph)	Wind Direction (degrees)	Start Data Acquisition	Source Initiated minutes	Fire Ignition minutes	Fire Extinguished minutes	Ventilate minutes	Halt Data Collection minutes
MV_23	9/2/99	TODCO Wall Board exposed to a methanol flame	TODCO wallboard. 10 cm x 30 cm (4 in x 1 ft). 846 ml (28.6 oz) methanol in a 11.43 cm (4.5 in) diameter pan	78	90	10	116	14:17:45	11.17	11.17	31.48	31.83	42.55
MV_24	9/2/99	Pipe Insulation exposed to a methanol flame	Calcium silicate insulation with glass cloth lagging. painted (45 cm, 17.7 in). 846 ml (28.6 oz) methanol in a 11.43 cm (4.5 in) diameter pan	78	90	5	100	15:18:17	10.47	10.47			41.78
MV_25	9/2/99	Personal care products such as rubbing alcohol, Ben-Gay, shaving cream, and Tinactin	Vapor from typical personal care products	78	92	8	114	16:14:50	10.10			20.78	30.50
MV_26	9/2/99	Background	10 + 20 minutes buttoned up, 10 minutes ventilation. 40 minutes total time	78	89	8	90	17:04:54				32.20	43.60
MV_27	9/3/99	Flaming bedding material	2 sheets, wool blanket, cover, pillow, mattress and ticking. All were 6" square except for ticking which covered 2 sides of the mattress. Fuel package was heated with a propane torch	80	86	4	32	9:58:21	17.03	17.03	33.83	34.38	44.50
MV_28	9/3/99	Smoldering cable	LSDSGU-9 cable 2 conductor wire + ground (91.4 cm (36 in.) long) ohmically heated with a 300 A arc welder	82	73	5	143	13:25:36	10.50				35.32
MV_29	9/3/99	Background	10 + 20 minutes buttoned up, 10 minutes ventilation. 40 minutes total time	83	74	5	128	11:54:05					

Four background tests, MV_03, MV_13, MV_26 and MV_29, and 2 sets of replicate tests were performed. MV_10 was a replicate of MV_ 05 and MV_11 was a replicate of MV_07. MV_00, the first background test, was not used in the analysis because of the interference from the RF transmissions. Caution should be taken when using the results from MV_ 05 and MV_10 for sensor stability considerations because the burning characteristics were different. However, the results from the 3 background tests, 2 heptane tests and the 2 tests on paper burning in the trashcan, MV_07 and MV_11 may be used to evaluate the stability of the sensors.

Figures 5-8 show the CO, CO_2, RH and temperature for the two selected heptane fires, MV_02 and MV_04. Figures 9-10 compare the CO and H_2 for the 2 trash can fires, MV_07 and MV_11. Figures 11-13 compare the CO, HCl and H_2S data between the 4 background tests, MV_03, 13, 26 and 29. These sensors were selected because they are possible candidates for the sensor array.

In studying the sensor data, the stability of the sensors is mixed. Fire tests are difficult to replicate unless all variables are controlled. However, in comparing the plots between the 2 heptane tests, background and the 2 trashcan fires the same sensors showed similar trends. The sensors maintained good performance through a majority of the tests.

6.2 Evaluation of Smoke Measurements

Table 5 shows the alarm times for the Simplex photoelectric and the Simplex ionization detectors on Boards A and B. The Simplex detectors were used as the benchmark for evaluating the early warning fire detector. Obscuration measurements from two of the Simplex detectors, one of each type, were obtained by using the specially designed hardware/software package. Table 5 includes the fire source ignition time or the time when the source was energized; the response times of the Simplex detectors at four different alarm levels (obscuration measurements) and the alarm times for the 4 Simplex detectors that were not hooked to the special device. Table 6 presents the performance of the Simplex detectors. The values signify the correct number of responses of an event type for a particular alarm level.

Table 5 - Smoke detector alarm times

Test No.	Ignition Time	Simplex Photo. Board A* 11% obs/m	8.2% obs/m	1.63% obs/m	0.82% obs/m	Simplex Photo. Board B* 11% obs/m	8.2% obs/m	1.63% obs/m	0.82% obs/m	Simplex Ion.Board A* 4.3% obs/m	1.6% obs/m	0.82% obs/m	Simplex Ion Board B * 4.3% obs/m	1.6% obs/m	0.82% obs/m	Simplex Alarms Photo 49	Photo 50	Ion 51	Ion 68
	min.	min.	min.	min.	min.	min.	min.	min.	min.	min.	min.	min.	min.	min.	min.	min.	min.	min.	min.
MV_00																			
MV_01	12.15	DNA	DNA	1.98	1.17	DNA	DNA	2.78	1.53	1.90	1.32	1.25	3.22	1.53	1.53	DNA	DNA	2.23	1.48
MV_02	10.63	12.35	11.47	2.77	1.73	13.00	11.77	2.18	1.67	3.20	2.40	2.18	1.95	1.52	1.45	11.96	11.85	2.38	1.95
MV_03																			
MV_04	11.47	14.60	14.02	2.53	2.25	15.05	14.17	1.73	1.52	3.63	2.25	2.10	1.73	1.37	1.37	14.32	14.18	2.77	1.67
MV_05	10.28	1.97	1.67	1.23	1.23	2.55	1.82	1.08	1.00	1.23	1.23	1.23	1.23	1.15	1.15	1.8	1.52	1.58	1.18
MV_06	10.50	10.50	10.43	8.53	8.38	7.28	7.15	6.85	6.55	10.28	9.55	8.53	7.43	7.15	6.70	11.02	7.68	DNA	6.65
MV_07	10.32	DNA	DNA	2.15	2.07	DNA	DNA	2.37	2.22	1.57	1.57	1.48	1.42	1.42	1.33	DNA	5.67	1.7	1.43
MV_08	10.27	32.43	31.55	17.25	16.73	32.07	31.18	28.27	27.47	37.12	35.37	34.27	36.02	35.95	34.92	25.9	32.15	30.63	35.98
MV_09	10.05	DNA	DNA	11.95	11.37	DNA	DNA	7.12	6.98	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA
MV_10	10.12	2.67	2.32	1.80	1.72	2.32	2.17	1.43	1.28	1.80	1.72	1.72	1.43	1.35	1.35	2.48	2.2	1.72	1.45
MV_11	10.13	DNA	4.88	2.62	1.82	DNA	5.25	2.77	2.48	1.53	1.38	1.30	1.30	1.17	1.17	DNA	DNA	0.95	0.88
MV_12	10.10	DNA	DNA	11.62	10.53	DNA	19.97	6.52	4.68	DNA	10.08	8.85	16.53	9.93	7.60	DNA	DNA	9.9	12.77
MV_13																			
MV_14	10.17	DNA	10.40	10.32	10.32	DNA	10.40	10.32	10.32	10.40	10.40	10.32	10.40	10.32	10.32	DNA	DNA	10.53	10.47
MV_15	10.13	DNA	DNA	DNA	21.20	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA
MV_16	10.78	DNA	20.52	1.43	0.98	DNA	DNA	0.33	0.33	0.70	0.48	0.40	0.92	0.48	0.40	DNA	DNA	2.33	1.58
MV_17	10.93	5.60	3.92	1.35	1.20	6.32	4.63	1.87	1.50	1.50	1.20	1.20	1.93	1.28	1.20	4.9	5.17	DNA	DNA
MV_18	10.53	DNA	1.62	1.40	1.40	DNA	1.68	1.40	1.10	1.53	1.47	1.40	1.25	1.10	1.10	1.97	1.62	1.42	1.13
MV_19	10.03	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA
MV_20	10.10	DNA	DNA	28.67	28.60	DNA	DNA	DNA	28.02	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA
MV_21	11.12	15.12	14.02	1.95	1.73	15.63	13.95	1.95	1.67	3.42	2.10	1.73	1.73	1.43	1.37	14.45	14.45	2.25	1.57
MV_22	10.17	4.75	1.62	1.25	1.10	DNA	DNA	DNA	10.68	4.83	4.75	4.75	DNA	DNA	8.48	5.08	DNA	2.37	DNA
MV_23	11.17	DNA	DNA	DNA	22.67	DNA	DNA	DNA	19.53	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA	15.03	DNA
MV_24	10.47	DNA	DNA	DNA	DNA	DNA	DNA	DNA	20.42	DNA	DNA	21.23	21.15	17.43	16.27	DNA	DNA	18.2	20.43
MV_25	10.10	DNA	DNA	DNA	10.72	DNA	DNA	9.85	9.70	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA	DNA
MV_26																			
MV_27	17.03	12.00	11.13	5.42	5.13	10.53	4.18	2.42	2.13	5.20	5.13	5.13	2.13	1.90	1.90	11.33	5.01	2.17	1.62
MV_28	10.50	6.10	6.03	6.03	5.97	5.52	5.52	5.52	5.52	5.82	5.75	5.75	5.75	5.52	5.45	8.87	5.87	6.78	6.22
MV_29																			

* Alarm times with respect to the initiation of the source
DNA = Did Not Alarm

Table 6. Detection Performance for Commercial Systems at the Shadwell Field Tests

Sensors	Setting	Fire	Nuisance	Background
PHOT-A	11% obs/m	9/18	5/7	5/5
	8% obs/m	12/18	4/7	5/5
	1.63% obs/m	15/18	2/7	5/5
	0.82% obs/m	17/18	1/7	5/5
PHOT-B	11% obs/m	9/18	6/7	5/5
	8% obs/m	13/18	5/7	5/5
	1.63% obs/m	14/18	2/7	5/5
	0.82% obs/m	17/18	1/7	5/5
ION-A	4.2% obs/m	14/18	4/7	5/5
	1.63% obs/m	14/18	3/7	5/5
	0.82% obs/m	15/18	3/7	5/5
ION-B	4.2% obs/m	15/18	4/7	5/5
	1.63% obs/m	15/18	4/7	5/5
	0.82% obs/m	15/18	3/7	5/5

As noted in Section 5.4, the instrumentation for these tests included five different means for measuring smoke; 1) the white light ODM, 2) the 670 nm laser ODM, 3) the 880 nm laser ODM, 4) the conventional ionization smoke detector (Simplex Ion), and 5) the conventional photoelectric smoke detector (Simplex Photo). Transient plots of the data from all of these instruments show both agreement and fairly large disparity between the various smoke measurements. In general, there was reasonable qualitative agreement between measurements. However, even when typical trends showed increases and decreases in smoke from the different sensors, the time scales did not always agree (i.e., some responded slower than others). In an effort to quantify the comparison of these measurements, three different time averaged values were calculated for each instrument during each test. The three values were

1. A one minute average from the time at which the first instrument started to show an increase in smoke,
2. A five minute average from the time at which the first instrument started to show an increase in smoke, and
3. A five minute average for the five minutes preceding the time at which the space was ventilated.

The different time periods were selected to provide the best possible comparisons of the smoke data. There were large variations in the development of smoke in different tests due to the nature of the various sources. For example, smoldering sources did not produce measurable levels of smoke until much greater times than for the flaming fires. The third average value was included since for many tests, smoke measurements agreed relatively well early in the test but diverged significantly toward the end of the 20 minute exposure period.

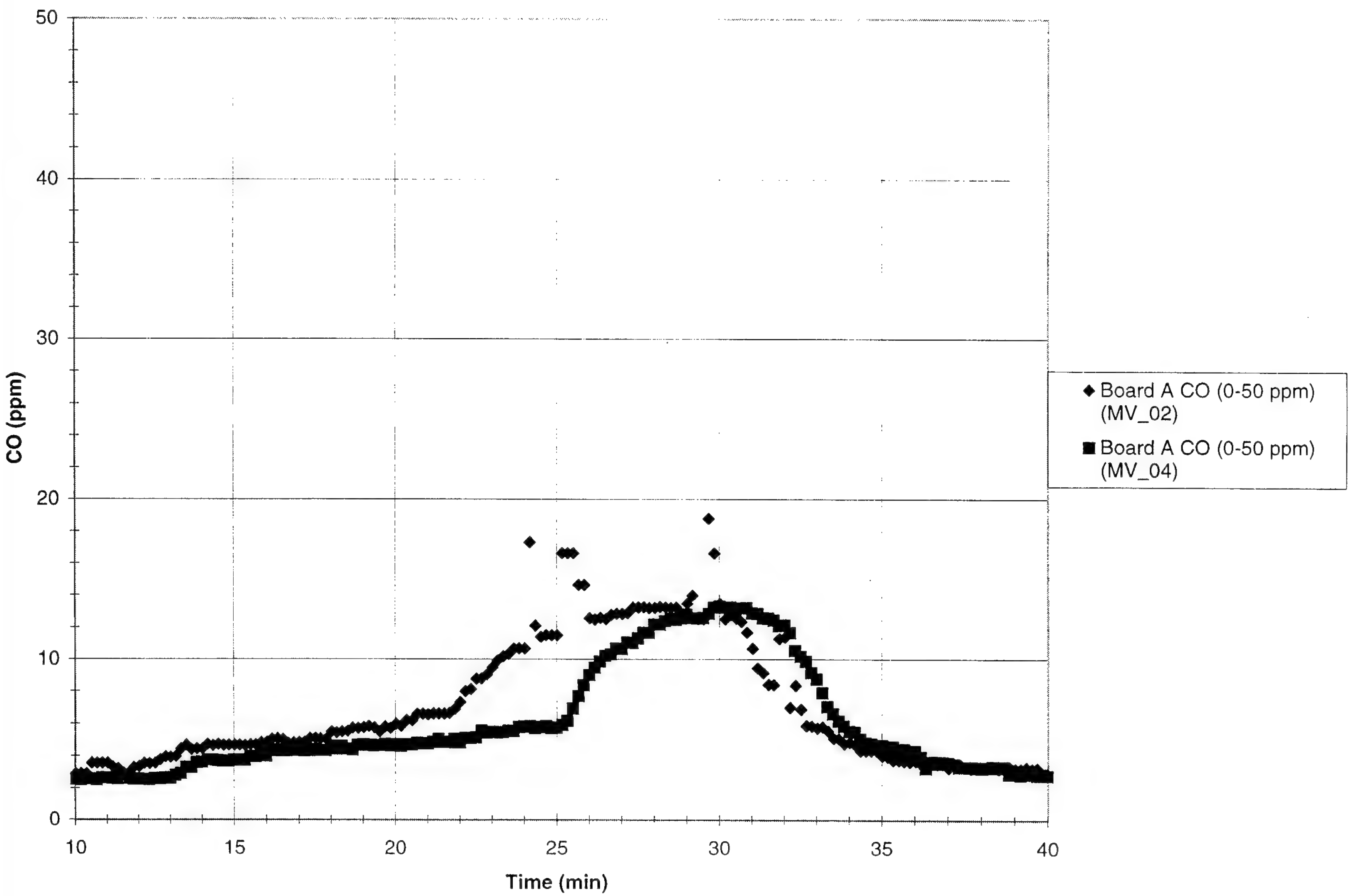

Figure 5 - CO concentrations of heptane tests

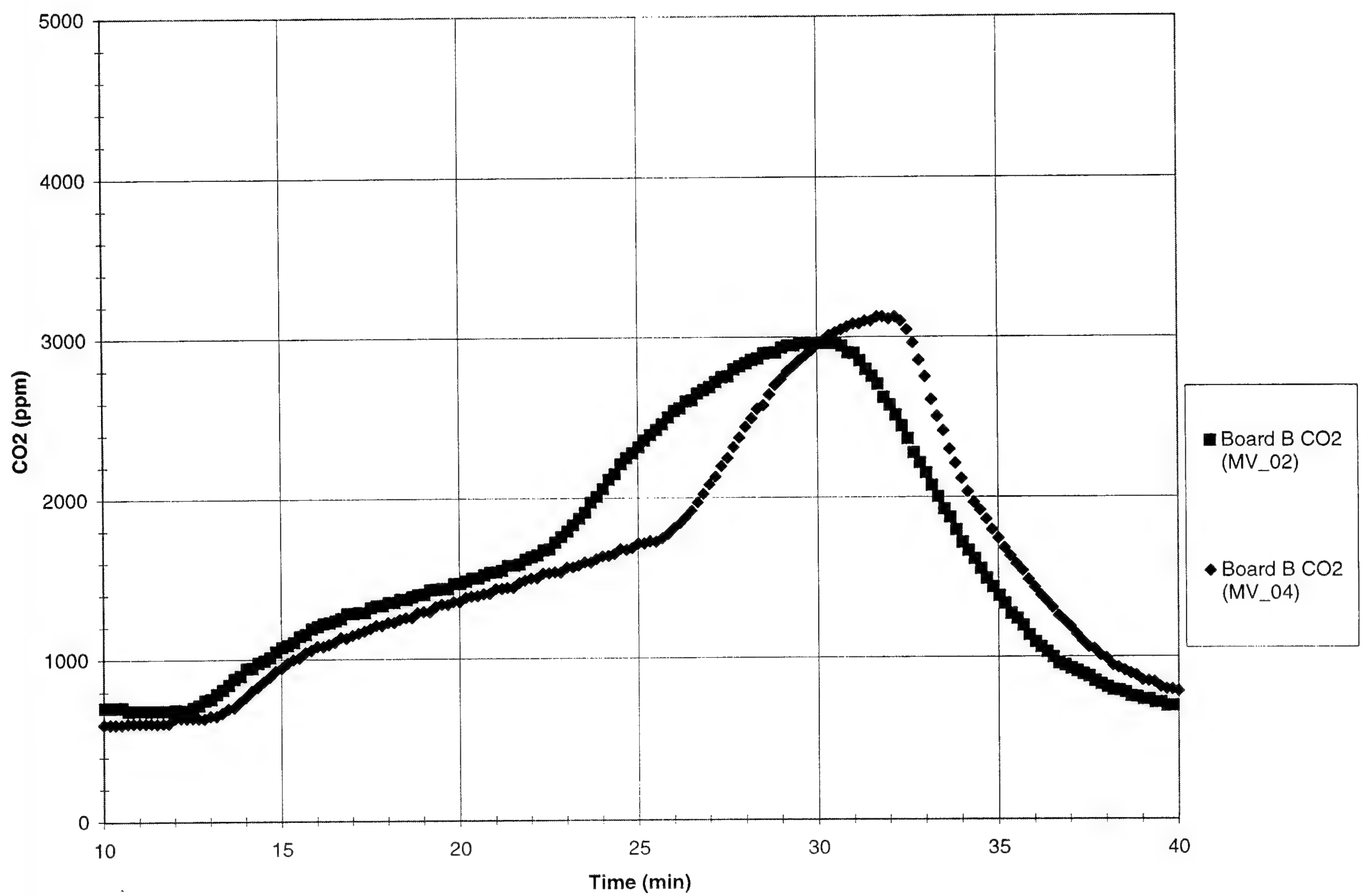

Figure 6 - CO_2 concentrations of heptane tests

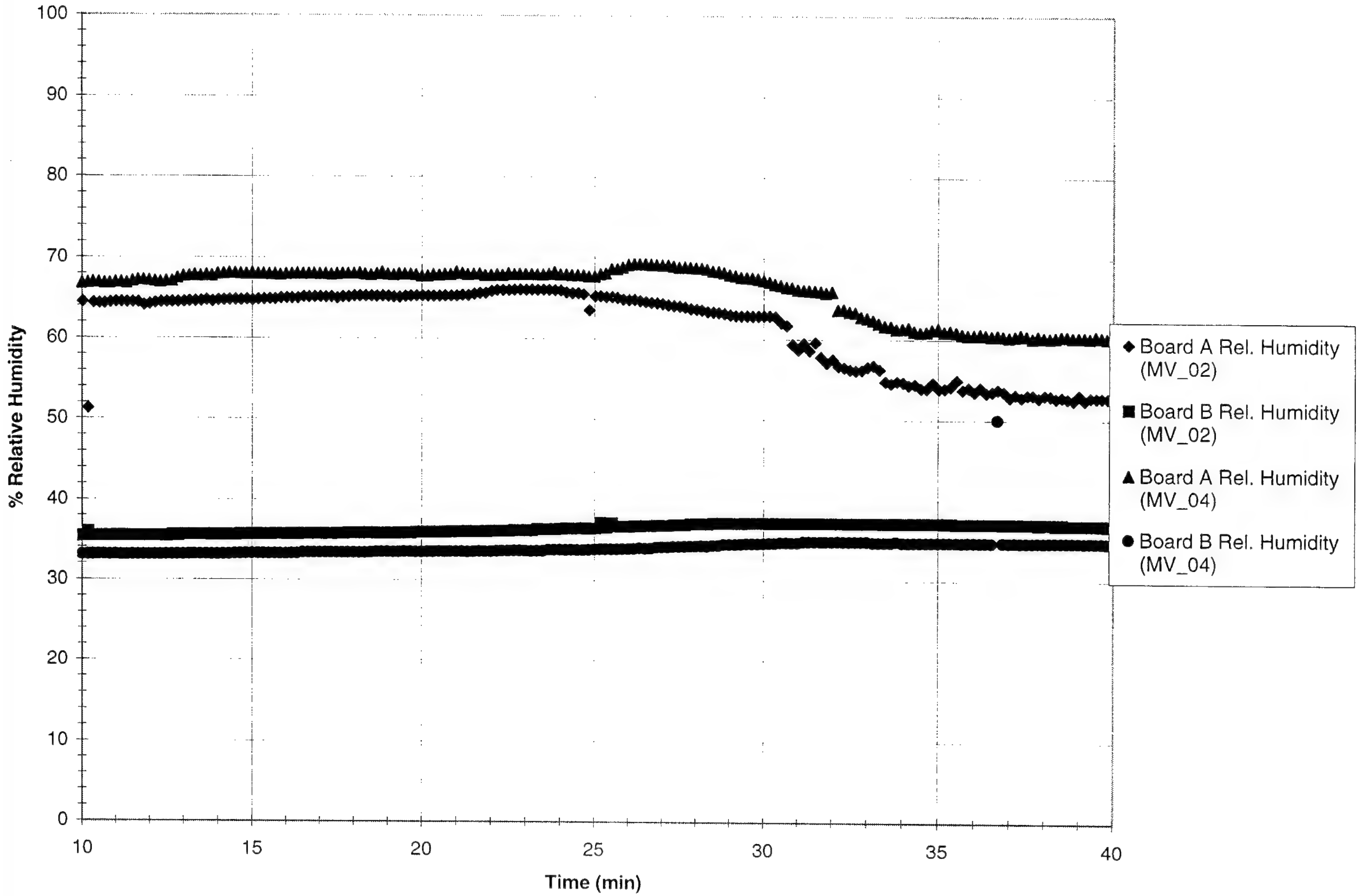

Figure 7 - Percent relative humidity of heptane tests

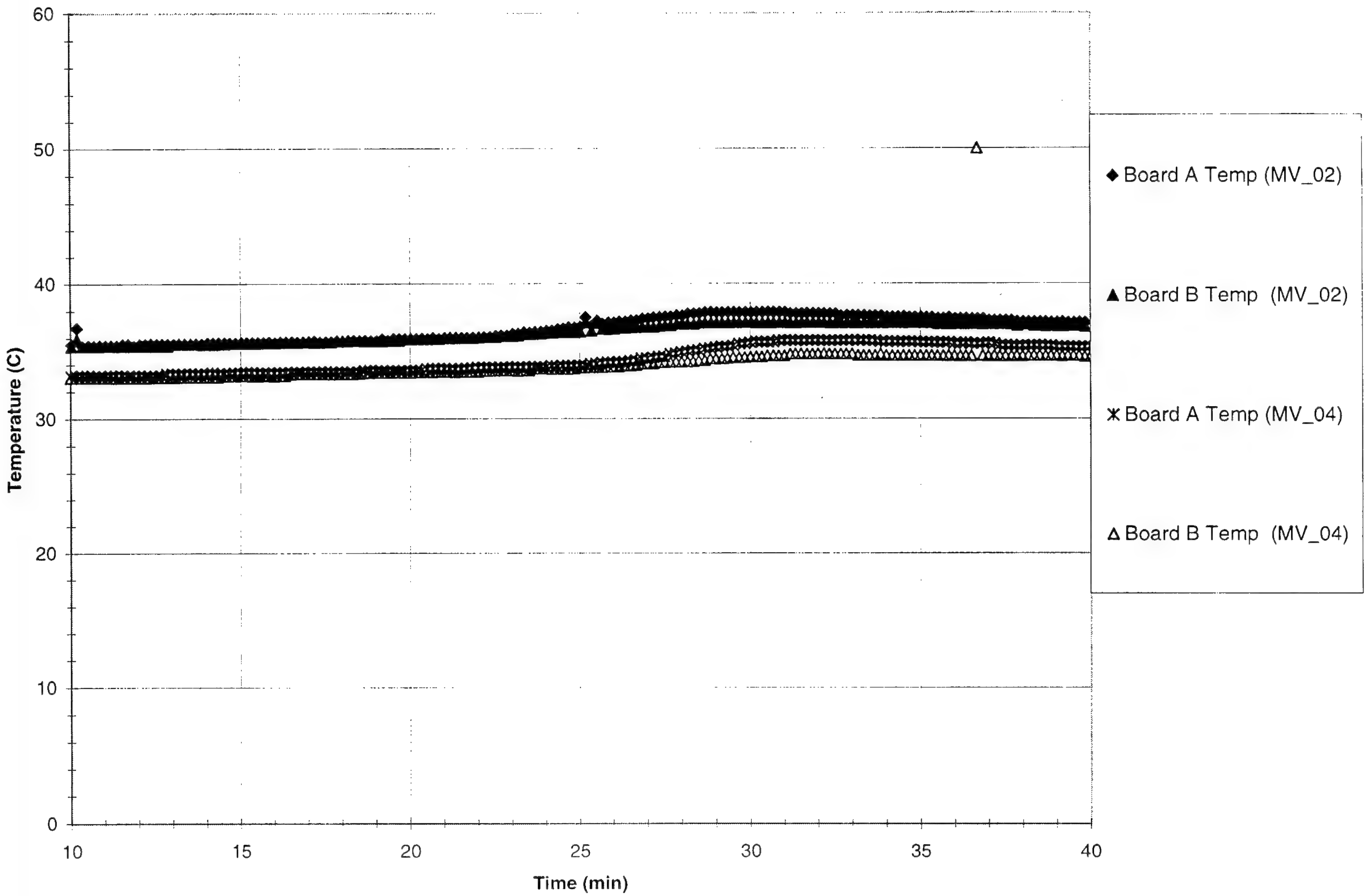

Figure 8 - Temperatures of heptane tests

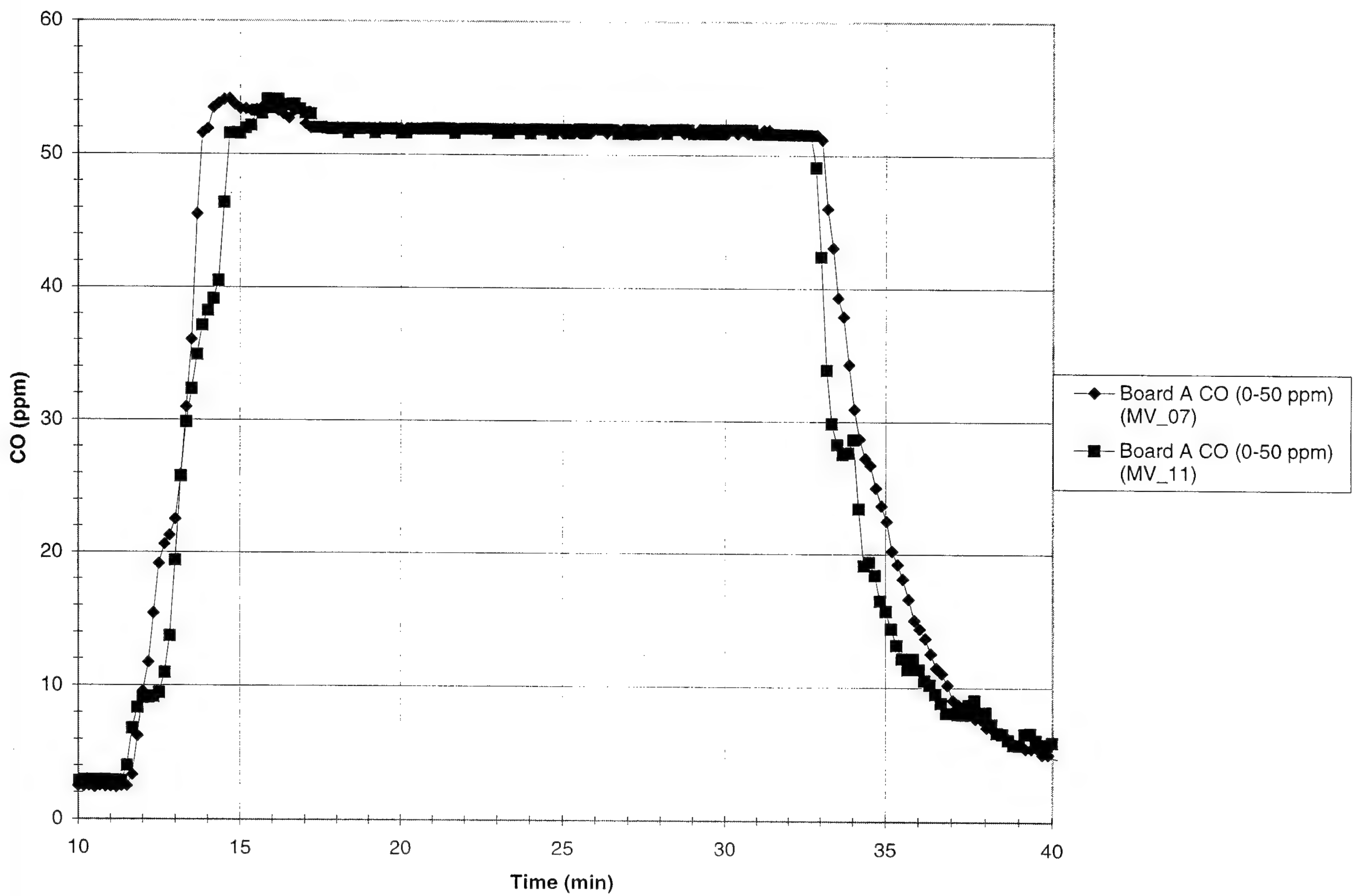

Figure 9 - CO concentrations of flaming paper in trashcan tests

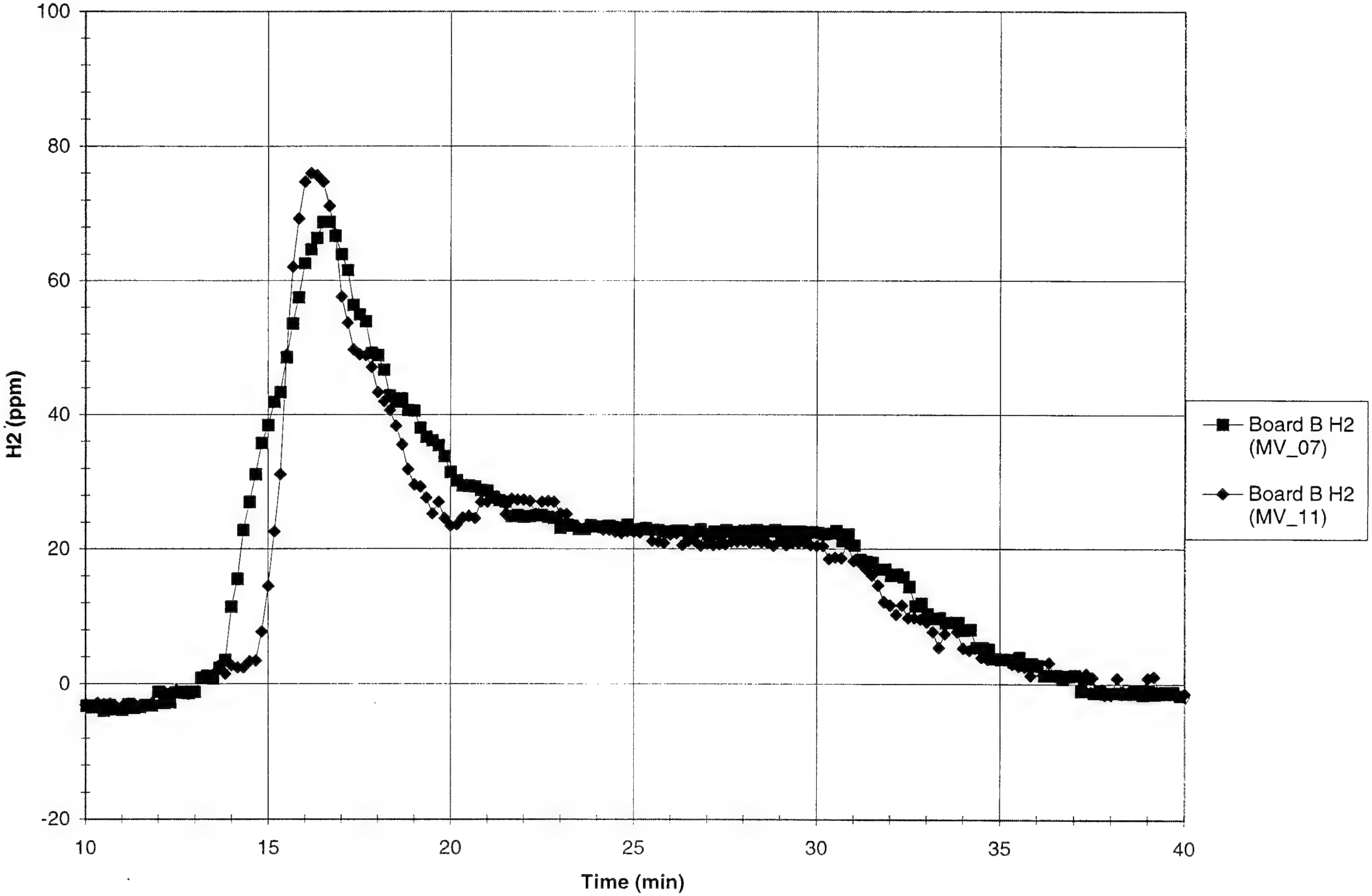

Figure 10 - H_2 concentrations of flaming paper in trashcan tests

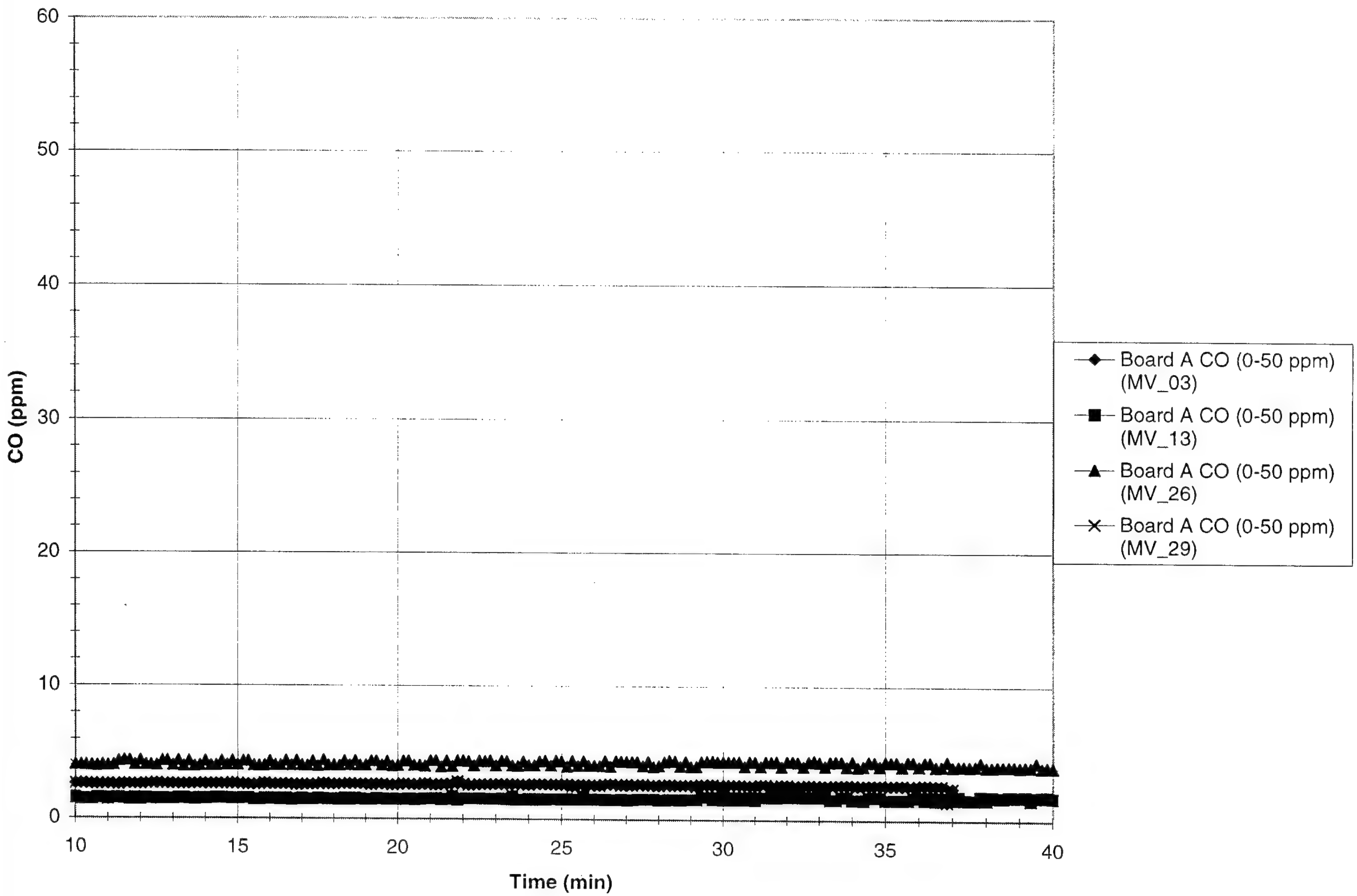

Figure 11 - CO concentrations of background tests

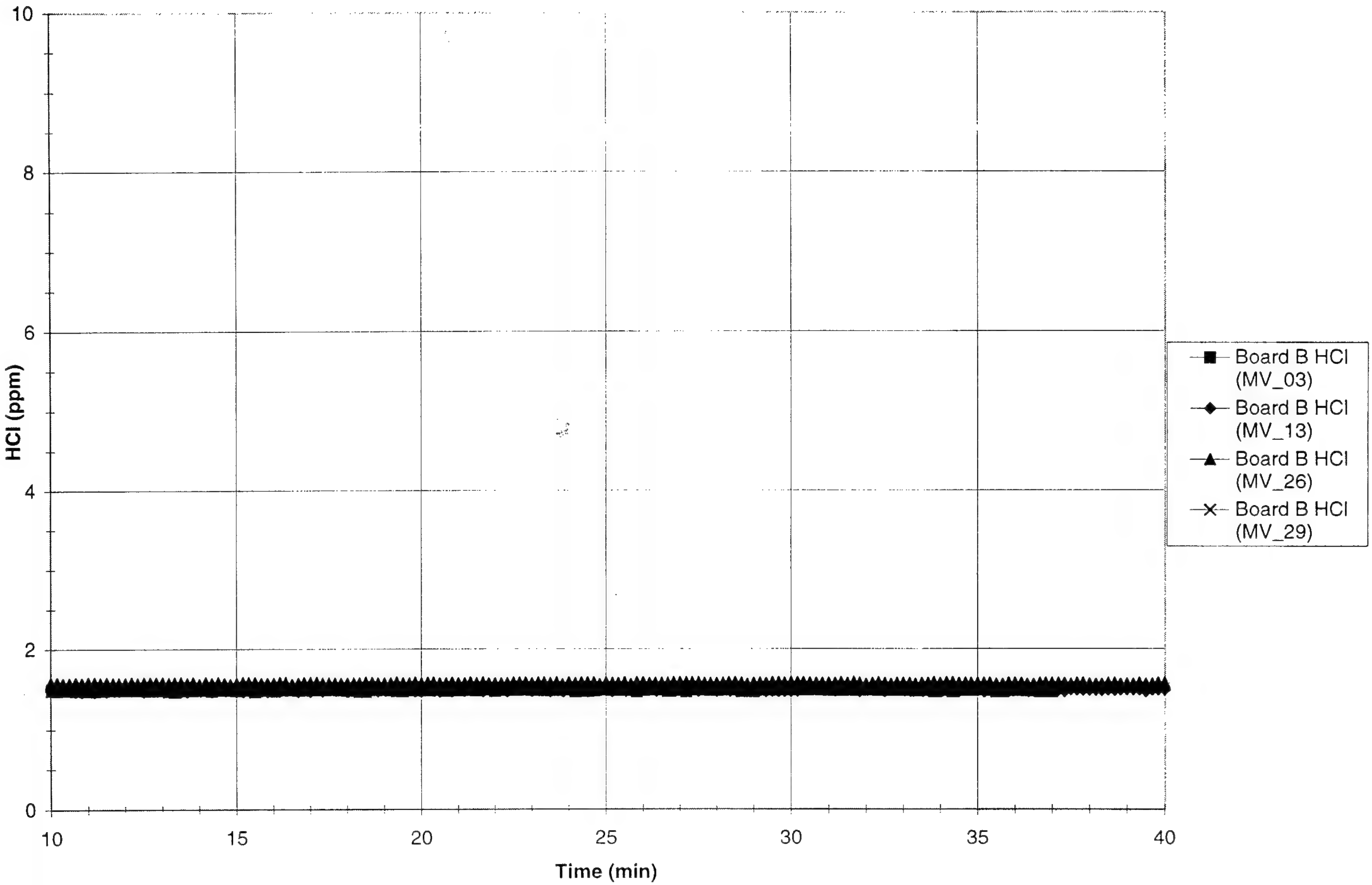

Figure 12 - HCl concentrations of background tests

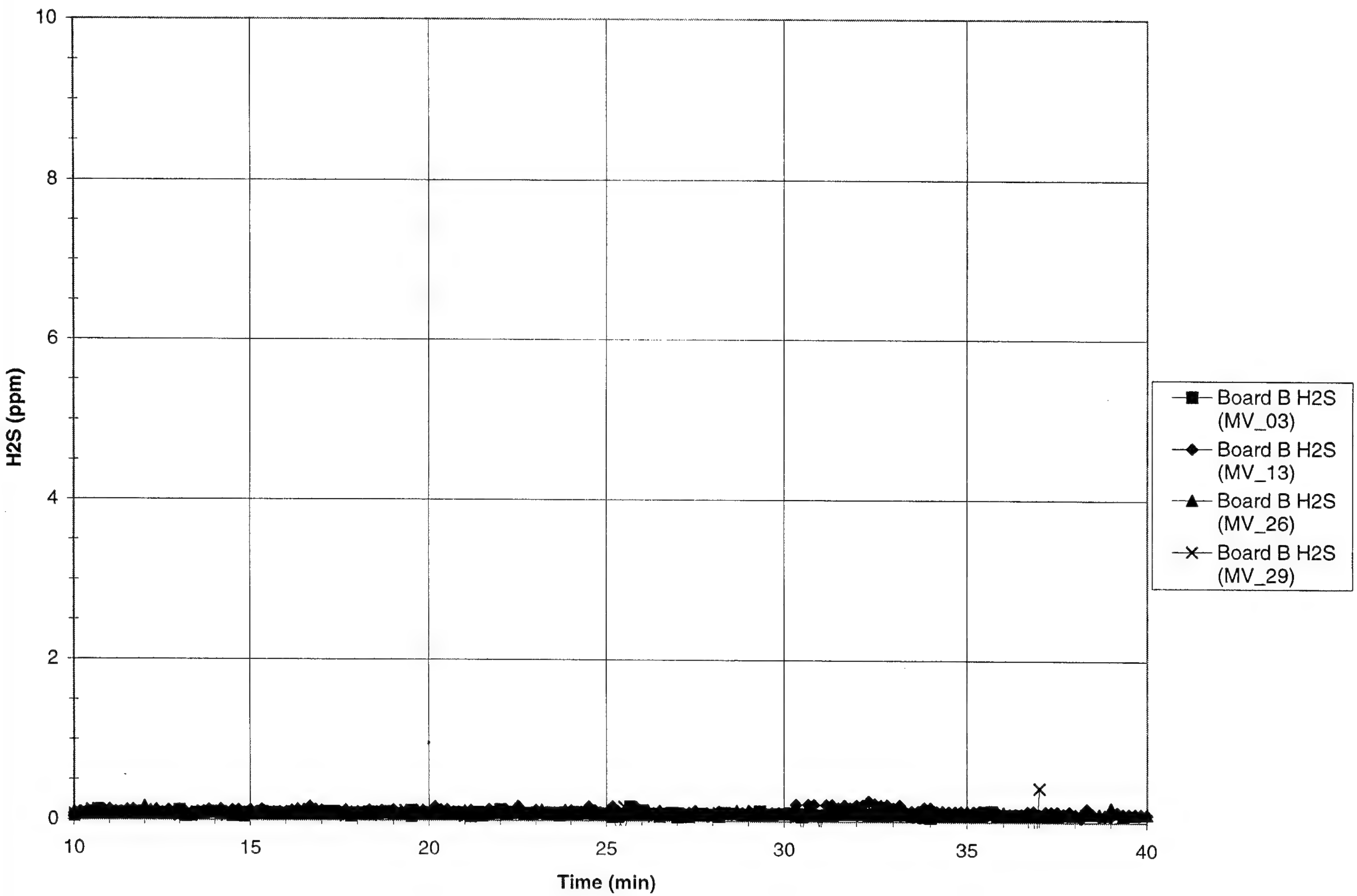

Figure 13 - H_2S concentrations of background tests

Table 7 presents a comparison of the time averaged smoke measurements for each of the instruments. The tests have been arranged to group similar sources together (e.g., flaming, smoldering, nuisance). The Table includes all tests except for the background tests and the personal care products and cleaning supply tests. These tests were not included since smoke was not produced. In a few instances, the Simplex Ion data show negative values. This is a result of the experimental correlation relating the detector output to smoke obscuration not being applicable to values below approximately 0.8 % obscuration per meter (0.25 %/ft). Negative values should be considered as equivalent to no measurable smoke. The maximum output values from the Simplex Ion and Photo detectors are 10.9 %/m (3.44%/ft) and 19.4 %/m (6.4%/ft), respectively. In numerous tests, the Simplex smoke detectors, particularly the ionization (Photo only in MV_06 and MV_28), saturated at the maximum value. The tests and time intervals affected were MV_06 (1-3), MV_16 (3), MV_17 (2,3), MV_02 (3), MV_04 (3), MV_21 (3), MV_05 (1-3), MV_10 (2,3), MV_07 (1,2), MV_11 (2), MV_18 (1-3), MV_28 (1-3), and MV_27 (2,3).

The white light ODM on Board A was very noisy; therefore only the data from Board B sensors are presented in Table 1. In six tests the white light ODMs had a noticeable baseline shift when the electrical sources were initiated (e.g., when the toaster, microwave or calrod was energized). It is believed that the baseline shift was due to a drain on the lamp when the source was turned on. The following tests were effected:

- Test 6, Toaster ~6-8 %/ft increase
- Test 8, Smoldering rags, calrod ~0.5 %/ft increase
- Test 9, Popcorn, microwave ~5-6 %/ft increase
- Test 14, Smoldering paper, calrod ~1 %/ft increase
- Test 15, Smoldering bedding, calrod ~1 %/ft increase
- Test 20, Smoldering pillow, calrod ~1 %/ft increase

The arc welder had no apparent effect on the ODMs.

Table 8 represents a subset of Table 7, in which all of the tests affected by the limitations of the Simplex maximum values or the ODM baseline shift have been excluded. In general, the data in Table 7 and 8 show that there is fairly wide scatter in the measurements. A study of Table 8, does not reveal any consistent trends from test to test of similar comparisons between any two device measurements.

Table 7. Comparison of time averaged smoke measurements from Board B

Test	Time Interval	White Light ODM (% obs/m)	670 nm Laser ODM (% obs/m)	880 nm Laser ODM (% obs/m)	Simplex Ion (% obs/m)	Simplex Photo (% obs/m)	Source Description
MV_09	1	16.04	3.25	5.19	-2.29	-0.06	Burning popcorn
	2	14.65	2.23	3.93	-2.13	3.13	
	3	7.89	0.75	1.78	-2.14	2.78	
MV_06	1	23.56	4.15	4.04	2.02	7.87	Burning toast
	2	38.45	43.97	37.86	8.39	17.05	
	3	27.17	37.87	31.97	10.44	19.39	
MV_22	1	1.58	2.16	0.54	-1.02	-0.17	Cigarette smoke
	2	1.30	2.34	0.30	-0.91	0.15	
	3	2.12	3.43	0.62	0.26	0.65	
MV_16	1	2.08	4.17	2.52	3.61	1.37	Cutting steel with acetylene torch
	2	0.66	1.86	1.02	7.04	1.40	
	3	2.79	6.14	2.08	10.53	6.05	
MV_12	1	-0.66	2.17	0.47	0.83	2.10	Welding
	2	-0.29	2.85	0.63	1.69	3.41	
	3	1.58	4.87	1.49	4.41	7.34	
MV_17	1	-0.11	2.99	2.18	3.19	1.26	Flaming fuel oil
	2	4.75	9.33	7.47	7.59	5.33	
	3	13.63	21.78	17.66	10.71	15.36	
MV_01	1	2.26	5.22	2.13	0.33	0.53	Flaming heptane
	2	4.34	7.87	4.62	3.82	1.98	
	3	7.79	20.85	7.90	9.71	5.03	
MV_02	1	-0.71	0.38	1.74	0.66	0.46	Flaming heptane
	2	2.48	5.08	5.04	5.84	2.74	
	3	13.99	31.44	19.98	10.75	13.81	
MV_04	1	3.37	4.53	3.50	5.00	1.94	Flaming heptane
	2	4.36	6.14	5.08	6.92	3.10	
	3	17.49	30.17	20.25	10.95	14.21	
MV_21	1	3.39	4.86	3.02	4.39	1.61	Flaming heptane
	2	5.95	7.89	5.64	7.32	3.72	
	3	11.01	16.61	11.86	10.23	8.32	
MV_05	1	11.14	10.70	11.48	10.66	8.33	Flaming oily rags
	2	13.37	13.16	13.71	10.96	10.48	
	3	13.65	21.72	14.21	10.61	11.06	
MV_10	1	5.92	7.53	5.52	8.52	5.62	Flaming oily rags
	2	10.17	12.04	9.70	10.21	13.34	
	3	11.22	14.77	10.86	10.65	11.93	
MV_07	1	2.33	-7.38	1.74	8.99	1.22	Flaming paper and cardboard
	2	4.55	3.39	3.04	9.90	4.37	

Test	Time Interval	White Light ODM (% obs/m)	670 nm Laser ODM (% obs/m)	880 nm Laser ODM (% obs/m)	Simplex Ion (% obs/m)	Simplex Photo (% obs/m)	Source Description
	3	3.07	21.24	1.74	1.57	1.95	
MV_11	1	1.20	-7.40	0.63	6.99	0.62	Flaming paper and
	2	5.09	0.52	3.15	9.69	4.50	cardboard
	3	3.53	32.79	1.33	2.39	1.99	
MV_18	1	5.37	6.82	3.41	6.84	5.22	Flaming wood crib
	2	5.33	6.34	3.06	9.95	5.56	
	3	4.27	5.15	1.90	10.74	4.11	
MV_28	1	12.83	17.55	14.04	-1.84	9.91	Smoldering cables
	2	9.36	13.94	11.70	-1.74	17.36	
	3	-7.68	1.04	0.60	-1.88	0.53	
MV_15	1	2.76	-0.68	-0.03	-2.22	-0.18	Smoldering bedding
	2	2.71	-1.02	-0.04	-2.25	-0.17	
	3	4.59	-1.92	0.15	-2.10	0.34	
MV_27	1	3.85	3.38	1.18	6.65	1.97	Smoldering bedding
	2	5.25	4.85	2.08	8.66	5.65	
	3	5.84	6.56	2.29	9.72	7.34	
MV_08	1	1.02	-4.27	1.36	-2.22	-0.18	Smoldering oily rags
	2	2.44	-2.62	2.95	-2.16	-0.18	
	3	21.04	27.43	32.22	-0.54	13.65	
MV_14	1	6.37	-4.34	2.76	10.51	5.73	Smoldering paper and
	2	6.60	5.96	2.99	9.45	4.32	cardboard
	3	4.66	37.94	1.47	3.81	2.15	
MV_20	1	3.27	0.85	-0.53	-2.15	-0.12	Smoldering pillow
	2	3.35	0.95	-0.36	-2.16	-0.15	
	3	3.07	2.40	0.07	-1.49	0.12	
MV_23	1	-0.24	0.76	-0.22	-2.12	-0.14	TODCO wall board
	2	-0.06	1.03	-0.14	-2.19	-0.14	exposed to a flame
	3	1.10	2.45	0.09	-0.27	0.64	
MV_24	1	0.26	1.73	0.05	1.44	0.17	Pipe insulation
	2	0.33	2.01	0.05	2.09	0.41	exposed to a flame
	3	-0.45	1.36	-0.05	-1.96	-0.13	

Table 8. Comparison of time averaged smoke measurements for reduced set of tests

Test	Time Interval	White Light ODM (% obs/m)	670 nm Laser ODM (% obs/m)	880 nm Laser ODM (% obs/m)	Simplex Ion B (% obs/m)	Simplex Photo B (% obs/m)	Source Description
MV_22	1	1.58	2.16	0.54	-1.02	-0.17	Cigarette smoke
	2	1.30	2.34	0.30	-0.91	0.15	
	3	2.12	3.43	0.62	0.26	0.65	
MV_16	1	2.08	4.17	2.52	3.61	1.37	Cutting steel with
	2	0.66	1.86	1.02	7.04	1.40	acetylene torch
MV_12	1	-0.66	2.17	0.47	0.83	2.10	Welding
	2	-0.29	2.85	0.63	1.69	3.41	
	3	1.58	4.87	1.49	4.41	7.34	
MV_17	1	-0.11	2.99	2.18	3.19	1.26	Flaming fuel oil
MV_01	1	2.26	5.22	2.13	0.33	0.53	Flaming heptane
	2	4.34	7.87	4.62	3.82	1.98	
	3	7.79	20.85	7.90	9.71	5.03	
MV_02	1	-0.71	0.38	1.74	0.66	0.46	Flaming heptane
	2	2.48	5.08	5.04	5.84	2.74	
MV_04	1	3.37	4.53	3.50	5.00	1.94	Flaming heptane
	2	4.36	6.14	5.08	6.92	3.10	
MV_21	1	3.39	4.86	3.02	4.39	1.61	Flaming heptane
	2	5.95	7.89	5.64	7.32	3.72	
MV_10	1	5.92	7.53	5.52	8.52	5.62	Flaming oily rags
MV_07	3	3.07	21.24	1.74	1.57	1.95	
MV_11	1	1.20	-7.40	0.63	6.99	0.62	Flaming paper and
	3	3.53	32.79	1.33	2.39	1.99	cardboard
MV_27	1	3.85	3.38	1.18	6.65	1.97	Smoldering bedding
MV_23	1	-0.24	0.76	-0.22	-2.12	-0.14	TODCO wall board
	2	-0.06	1.03	-0.14	-2.19	-0.14	exposed to a flame
	3	1.10	2.45	0.09	-0.27	0.64	
MV_24	1	0.26	1.73	0.05	1.44	0.17	Pipe insulation
	2	0.33	2.01	0.05	2.09	0.41	exposed to a flame
	3	-0.45	1.36	-0.05	-1.96	-0.13	

7. SUMMARY

This report documents the test setup and results from the smoke detectors used during this test series with results from the multivariant data analysis to follow in a later report.

Based on the data collected, the electrochemical sensors that are being considered as part of the sensor array did tend to be stable. The smoke instruments showed both agreement and fairly large disparity between the various smoke measurements. However, there was a tendency toward reasonable qualitative agreement between measurements.

~~8.0 References~~

Ref: (a) Carhart, H.W., Toomey, T.A., and Williams, F.W., "The ex-USS SHADWELL Full-scale Fire Research and Test Ship," NRL Memorandum Report 6074, revised January 20, 1988, reissued 1992.

(b) Gottuk, D.T., Hill, S.A, Schemel, C.F., Strehlen, B.D., Rose-Pehrsson, S.L., Shaffer, R.E., Tatem, P.A., and Williams, F.W., "Identification of Fire Signatures for Shipboard Multi-criteria Fire Detection Systems," NRL Memorandum Report 8386, June 18, 1999.

(c) TSI Incorporated, A Final Report Smoke Detector, IRLED, . prepared for David Taylor Naval Ship R&D Center, January, 1988.

Appendix A

Checklists

Multicriteria Fire Detection Testing
Daily Checklist

Sheet 1 of 2 **Date** ____________

VIDEO/AUDIO SYSTEM

_____ Video cameras on
_____ Video display monitors on
_____ Video cassette recorders on, tapes loaded, counters reset
_____ Date/Time generators on, adjust dates or times as necessary

INSTRUMENTATION

_____ Data acquisition systems on
_____ Synchronize computer clock with date/time generators
_____ Data collection program loaded and running
_____ Thermocouples: Display check _____ Full op check _____
_____ Optical density meters: Op check _____ Calibration check _____
_____ Gas analysis systems:
Lines blown down, water traps drained _____
Filters checked _____ replaced _____
Loop #1
Zero/span _____
Ambient conditions _____
Flow rates set _____
Loop #2
Zero/span _____
Ambient conditions _____
Flow rates set _____
Loop #3
Zero/span _____
Ambient conditions _____
Flow rates set _____
Loop #4
Zero/span _____
Ambient conditions _____
Flow rates set _____

Multicriteria Fire Detection Testing
Daily Checklist

Sheet 2 of 2 **Date** ____________

MECHANICAL SYSTEMS

_____ Main fire pumps on
_____ Backup fire pump checked

SAFETY SYSTEMS

_____ Protective clothing in well
_____ OBAs on hand in well
_____ Backup handlines flowed and positioned
_____ PKP extinguisher staged
_____ Ignition torches staged
_____ Two boats available and ready
_____ Coast Guard notified

TEST DAY CONCLUSION

_____ Backup data files to magnetic tape and zip disk
_____ Video cameras, monitors, and recorders off
_____ MassComp powered down and monitors off
_____ Control room power supplies off
_____ Clean and recalibrate ODMs as needed
_____ Secure suppression system water supply

Multicriteria Fire Detection Testing
Test Checklist

Test Name:__________________ Date:

Description: ____

____

Ambient Conditions
Temperature:______ (F) Rel. Humidity:______ (%)

Wind Speed:______ (mph) Wind Direction:__________ (degrees)

__________ Test area photographed

__________ Make announcement:
"Attention all personnel, fire testing is in progress. All personnel must clear Frames 15 to 29 on the main, second and third decks."

__________ Closure plan in effect.

__________ Gas sampling pumps on, flows set

__________ Radio check
- ___ Safety officer 1
- ___ Safety officer 2

__________ Test compartment evacuated (except for fueling personnel)

__________ Fire main charged

__________ Start data acquisition - Masscomp (10 minutes background data)

__________ Start videos

__________ Ignite pan

__________ Fire ignition

__________ Test called away

Test Name:______________________ Date:__________

_________ Fire extinguished

_________ Stop video recorders

_________ Collect 10 minutes of post fire data

Post Test Turnaround

_________ Commence post fire shutdown as directed

_________ Safety team open doors/hatches to vent test area completely

_________ Monitor temperature and oxygen concentration activity (computer readout)

_________ Halt data collection systems

_________ Secure gas analyzer pumps

NOTES:

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Appendix B

Event timelines

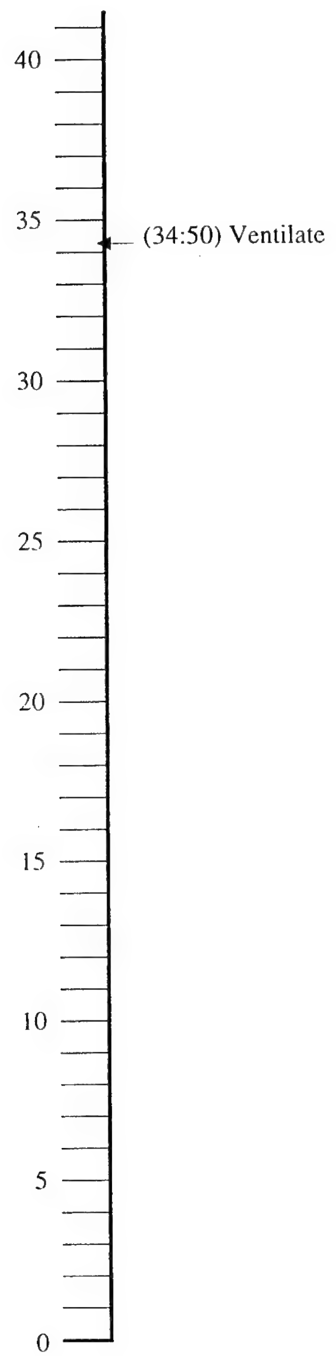

Fig. B1 – Timeline of events for Test MV-00

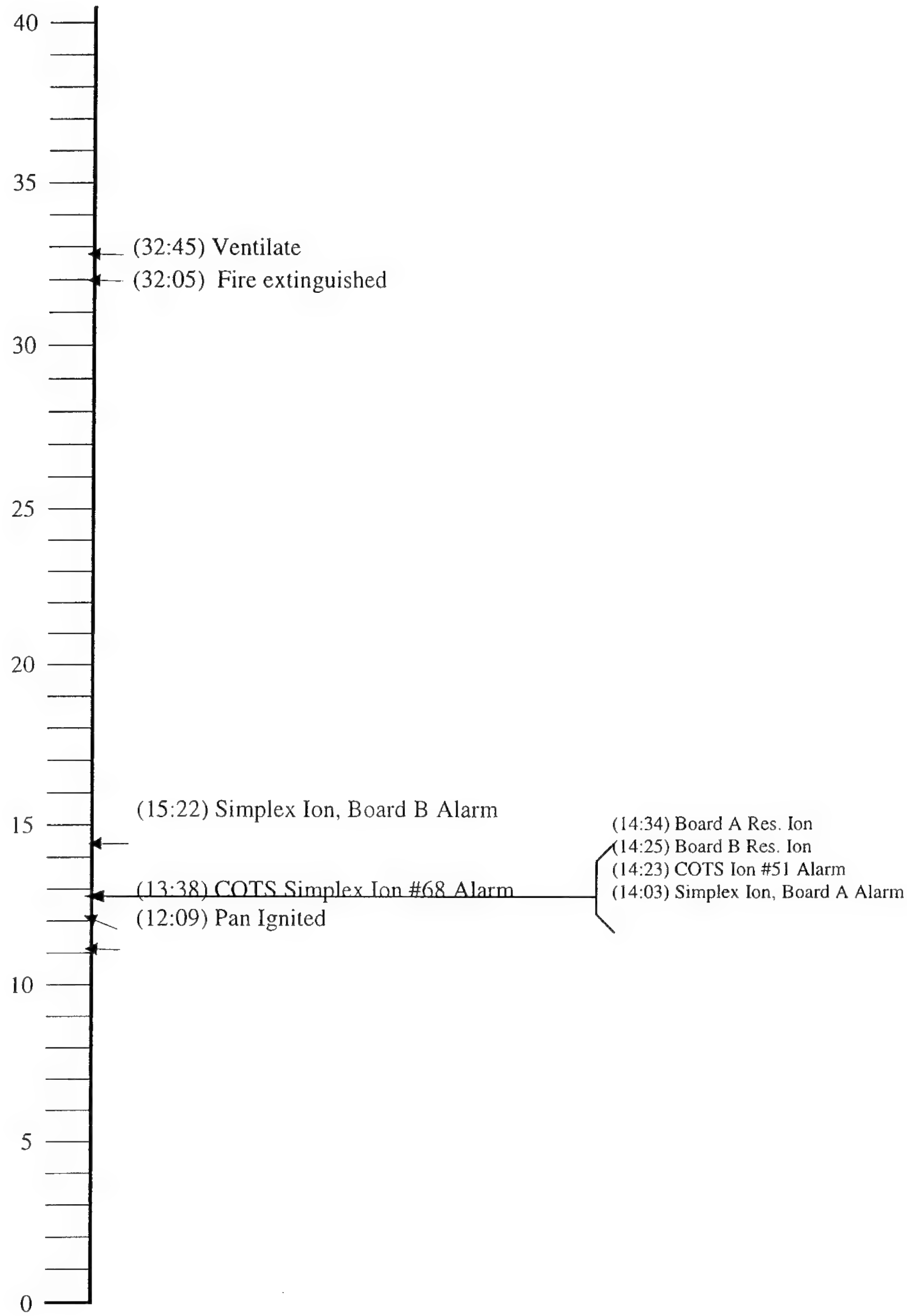

Fig. B2 – Timeline of events for Test MV-01

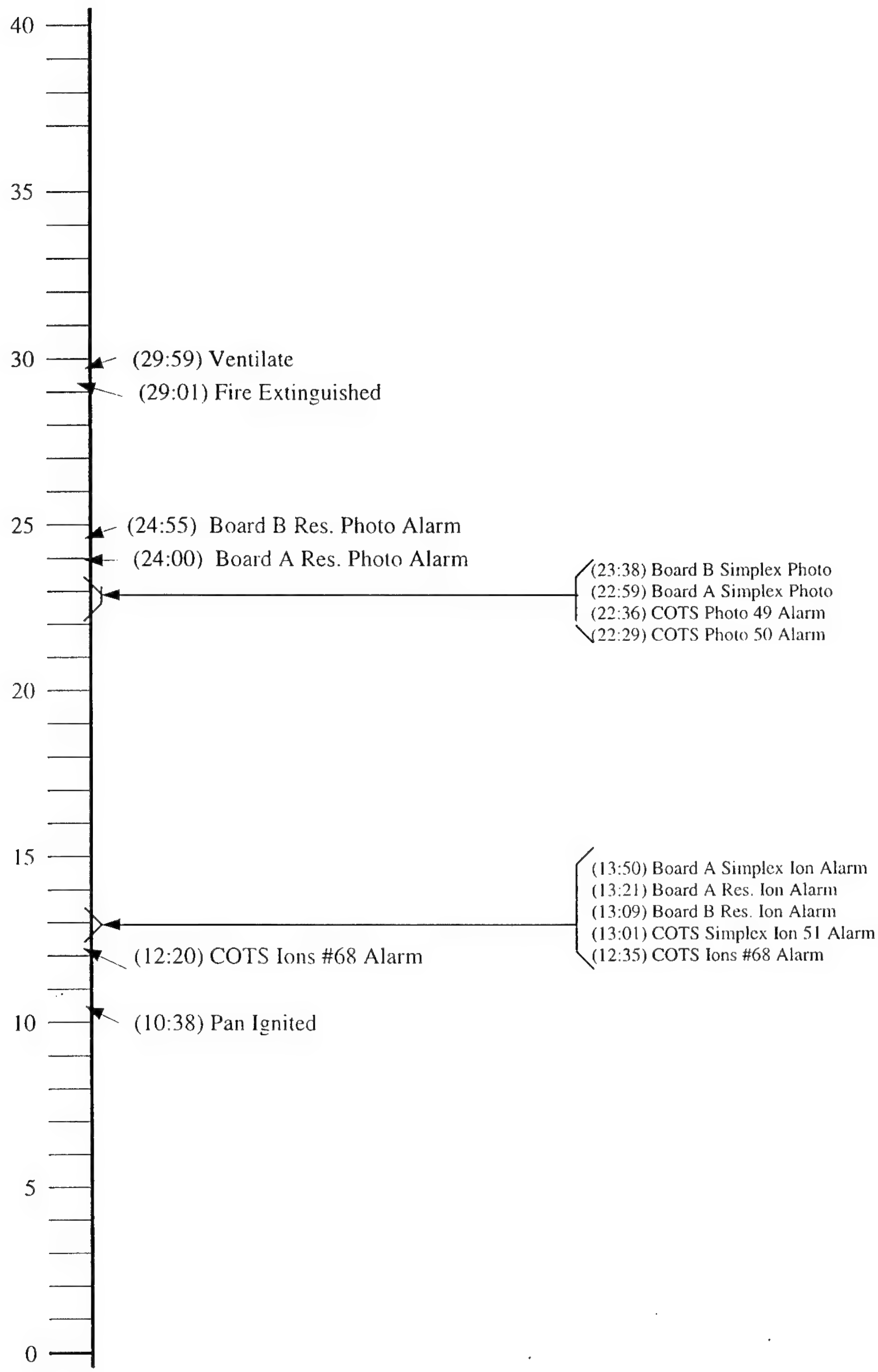

Fig. B3 – Timeline of events for Test MV-02

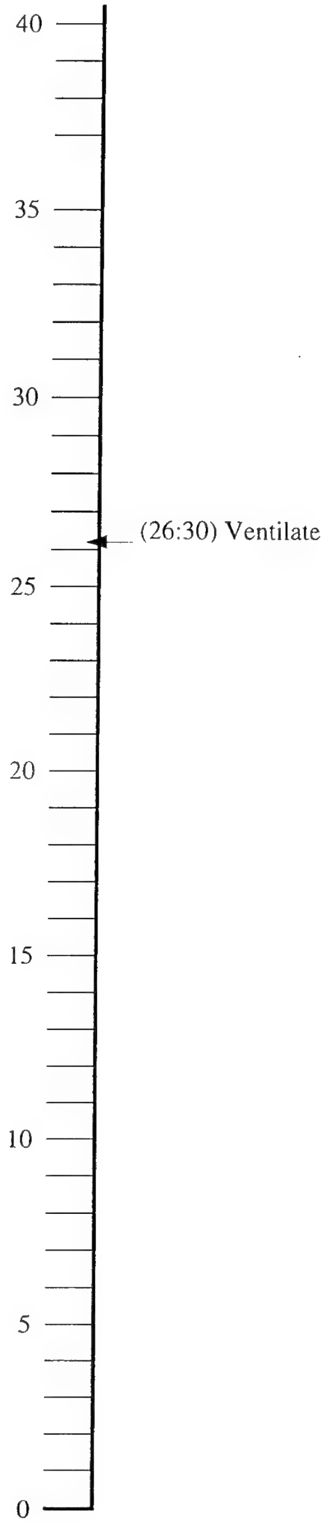

Fig. B4 – Timeline of events for Test MV-03

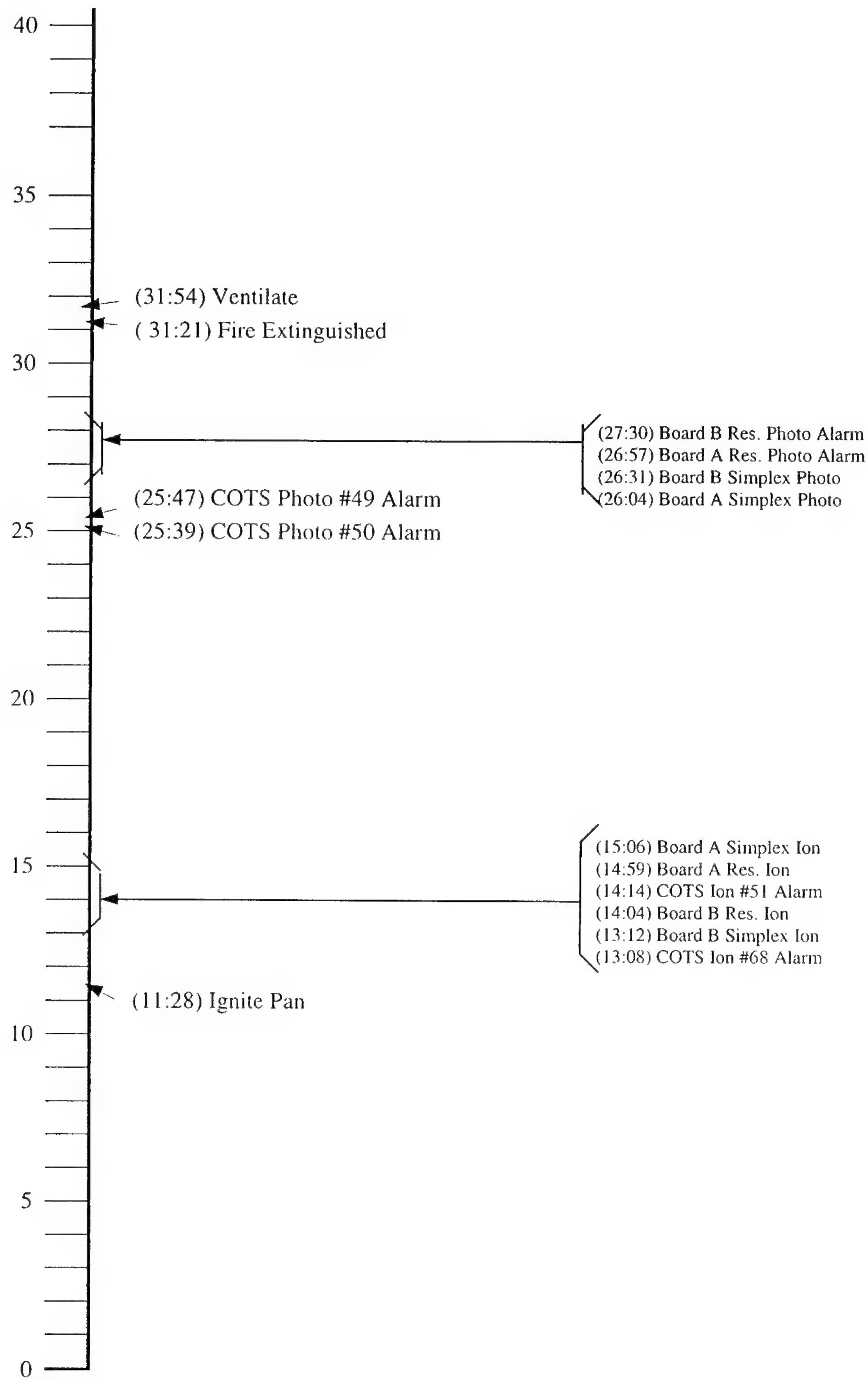

Fig. B5 – Timeline of events for Test MV-04

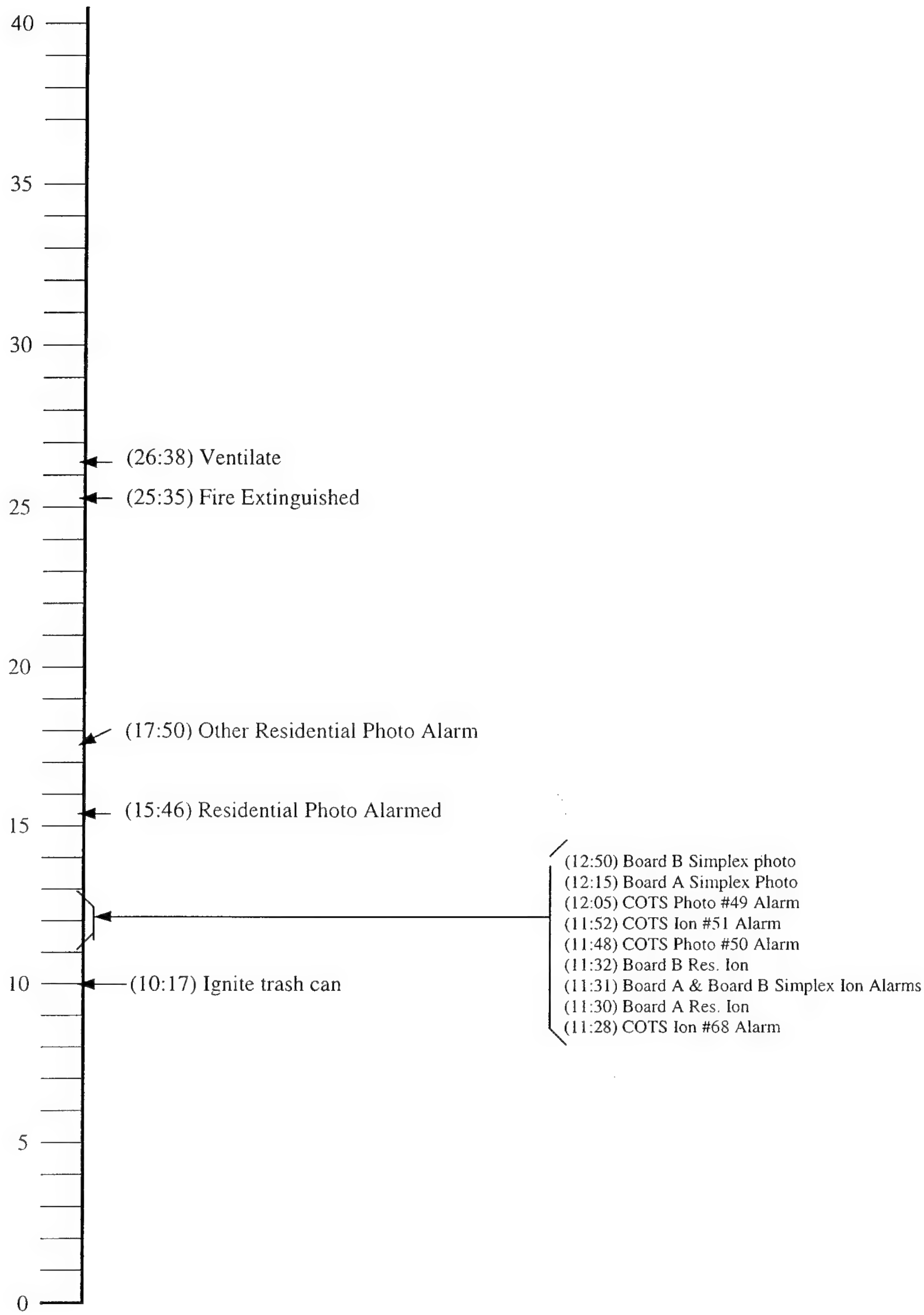

Fig. B6 – Timeline of events for Test MV-05

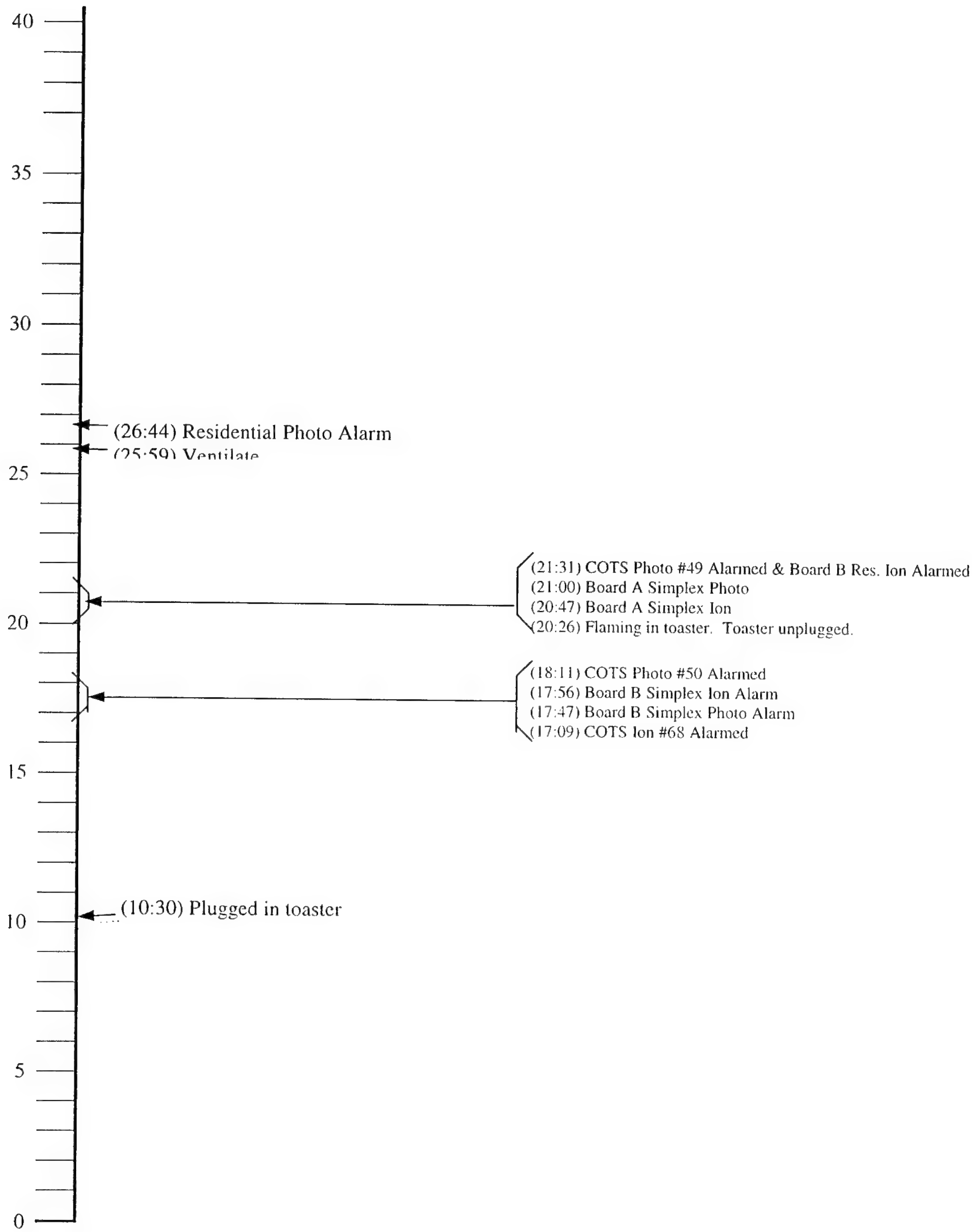

Fig. B7 – Timeline of events for Test MV-06

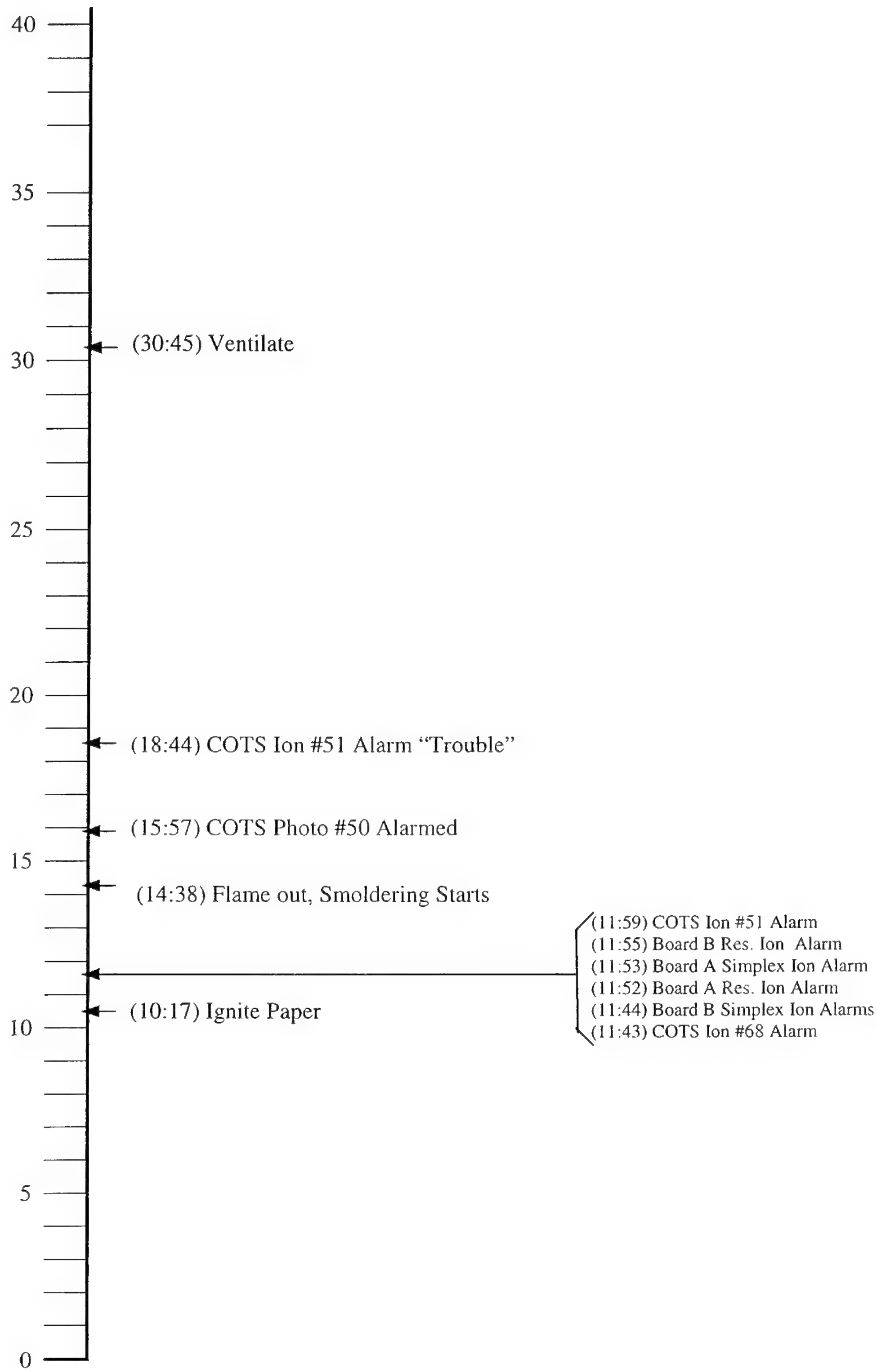

Fig. B8 – Timeline of events for Test MV-07

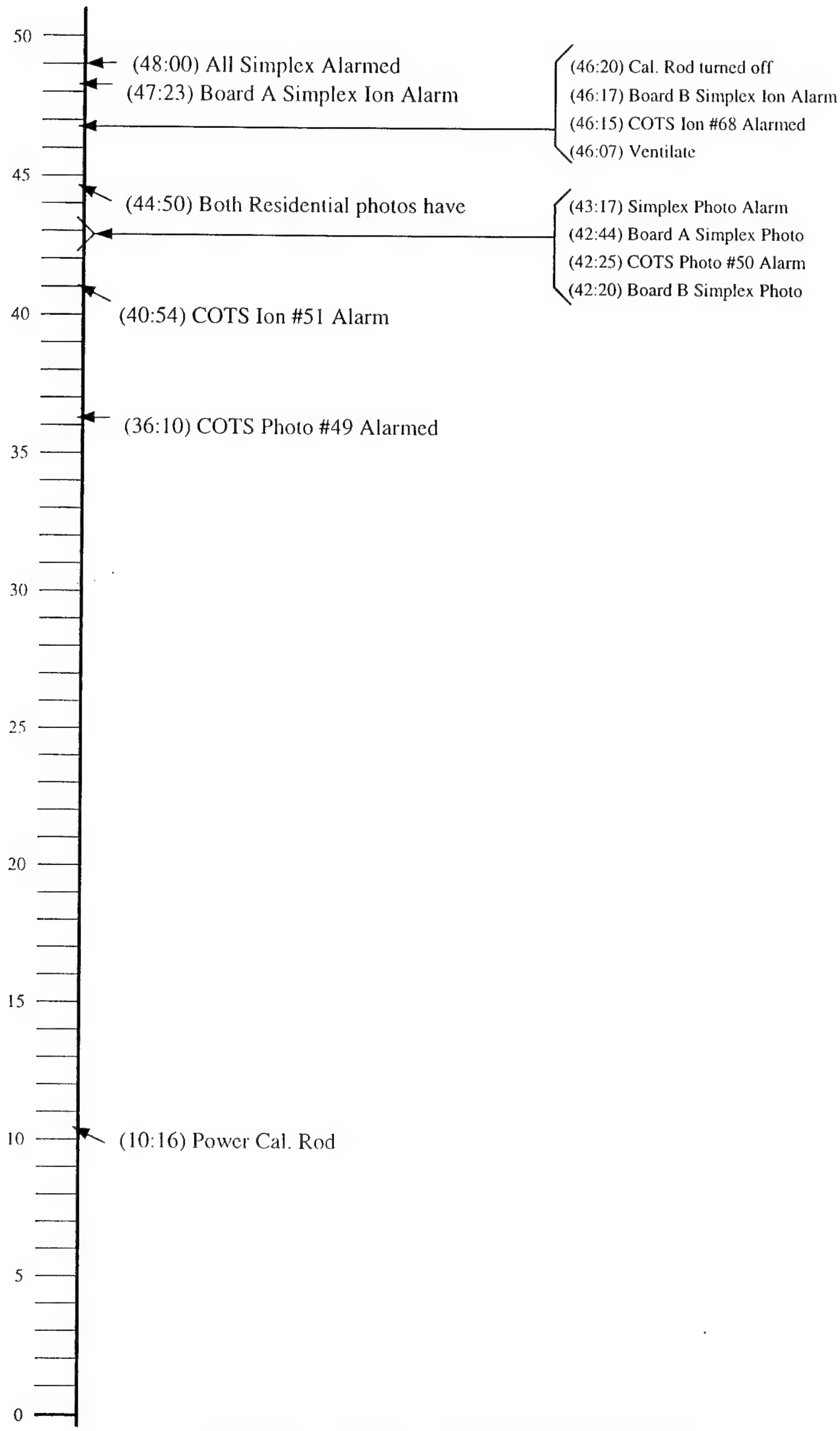

Fig. B9 – Timeline of events for Test MV-08

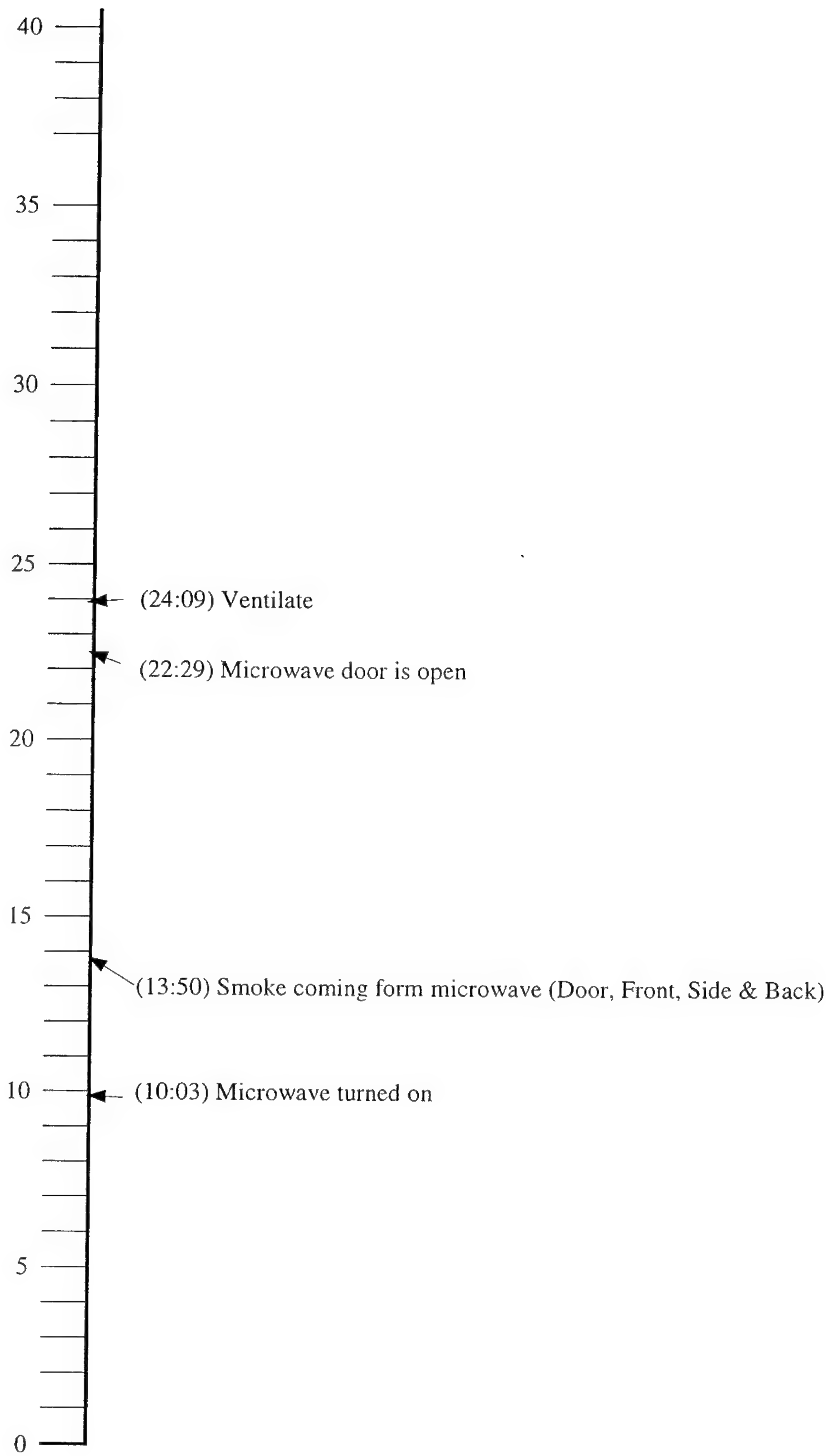

Fig. B10 – Timeline of events for Test MV-09

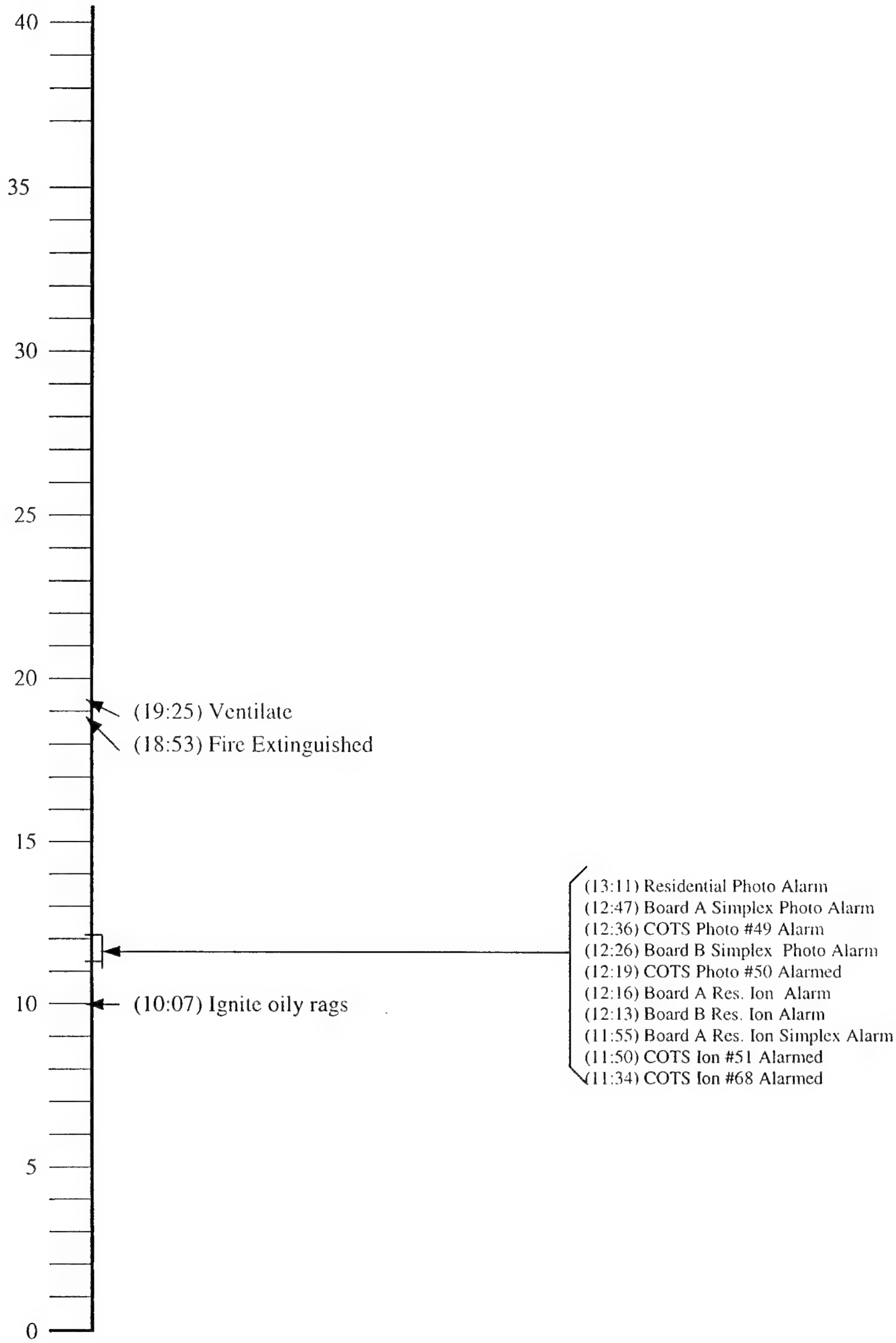

Fig. B11 – Timeline of events for Test MV-10

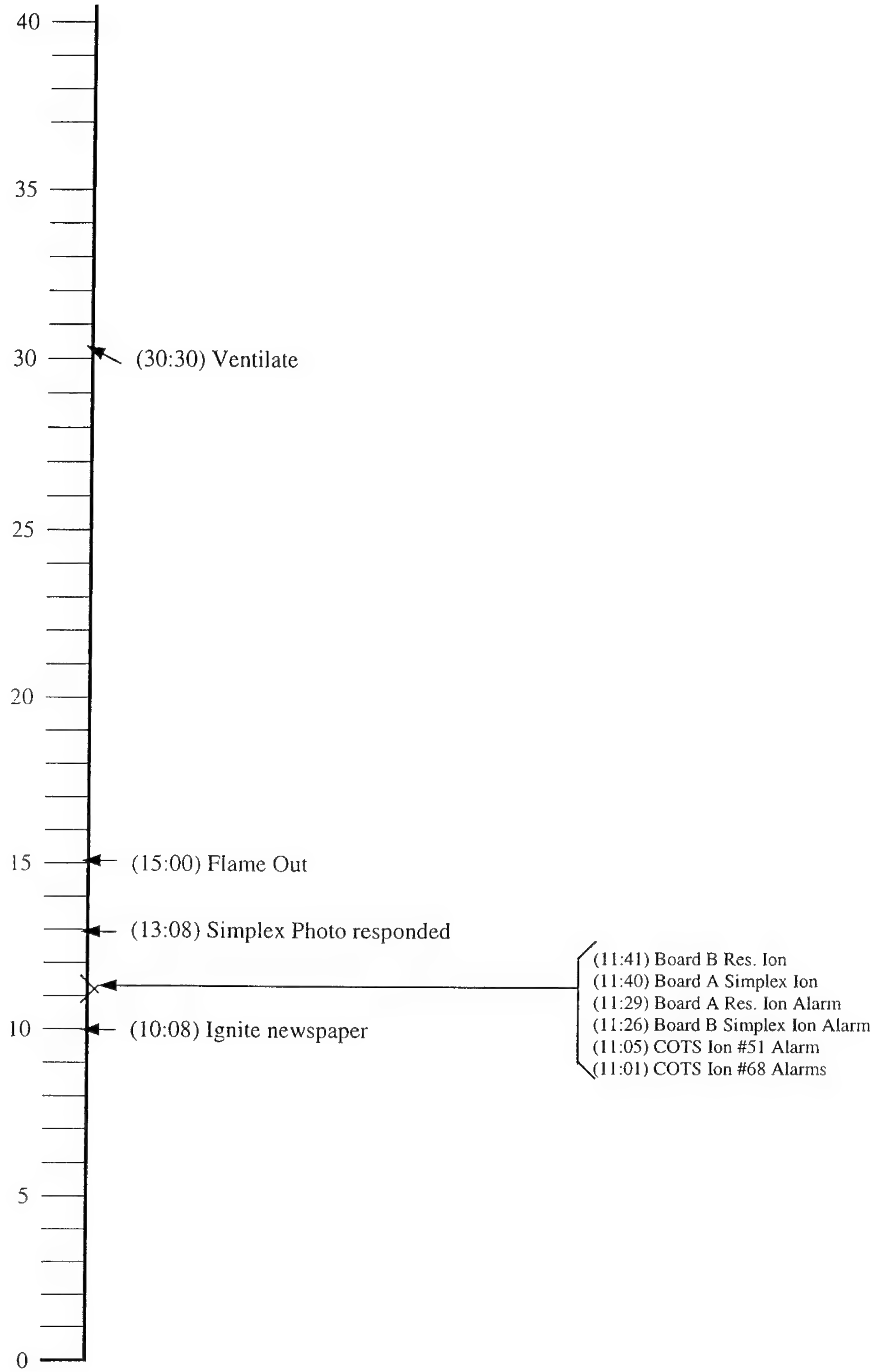

Fig. B12 – Timeline of events for Test MV-11

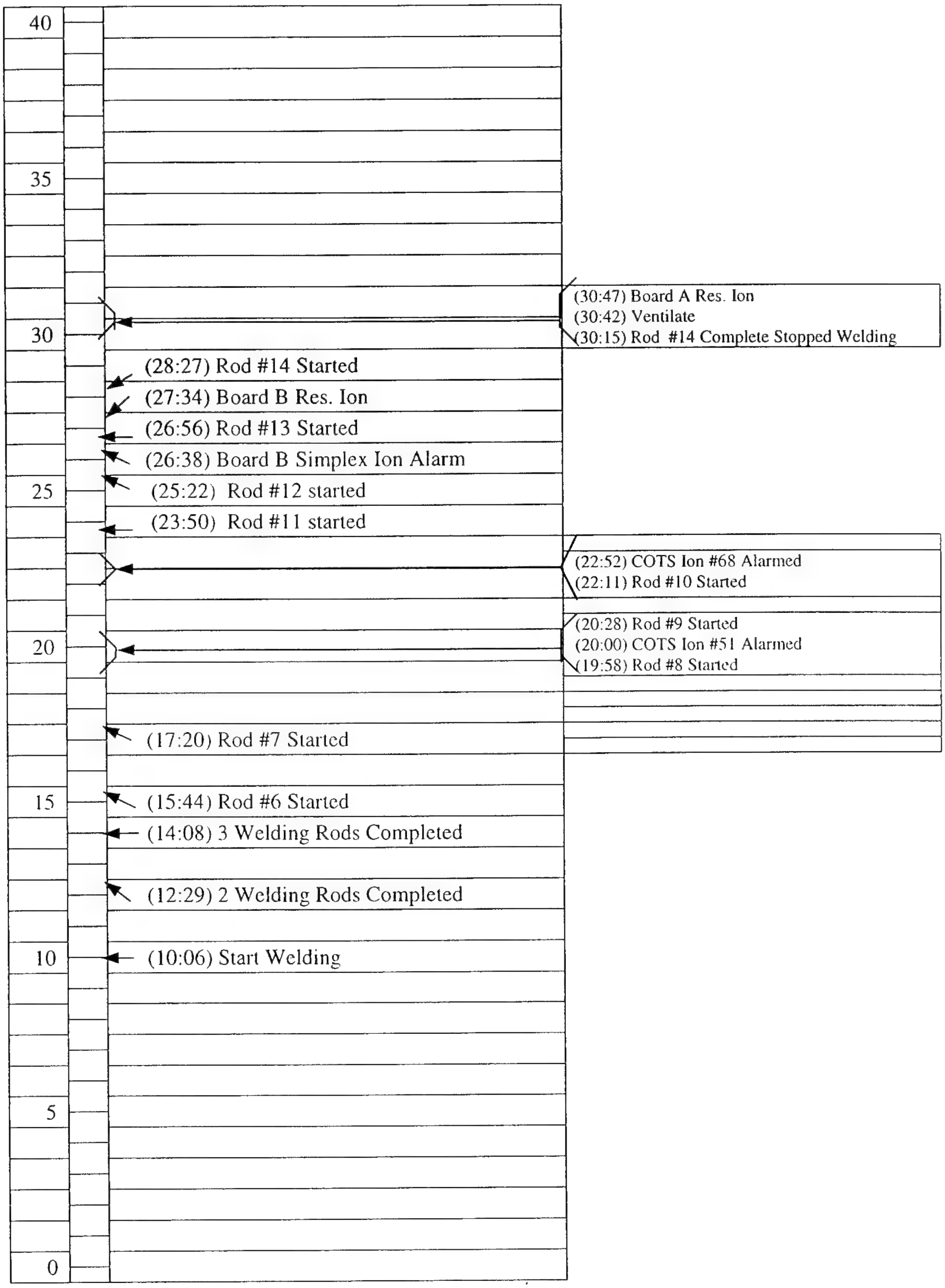

Fig. B13 – Timeline of events for Test MV-12

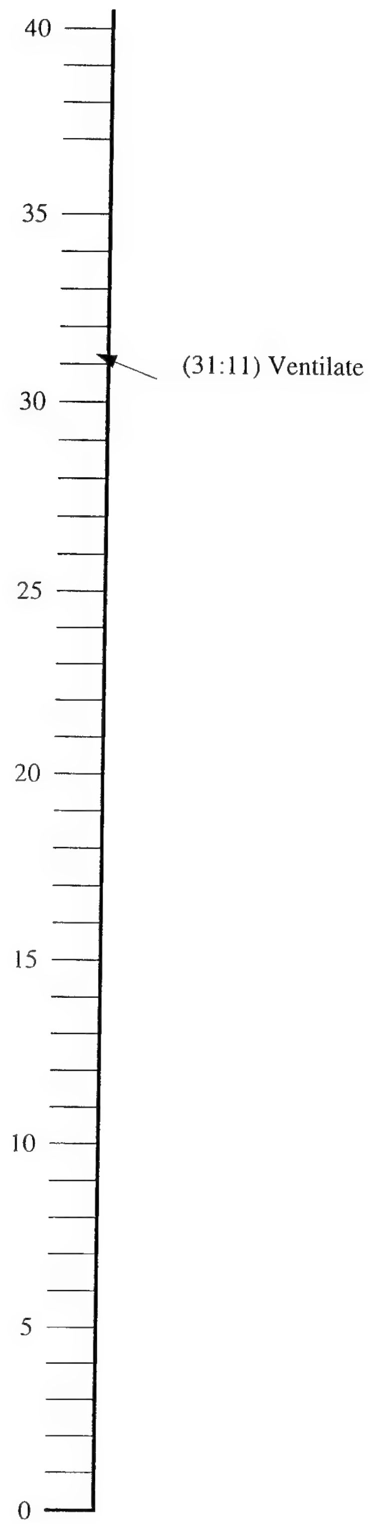

Fig. B14 – Timeline of events for Test MV-13

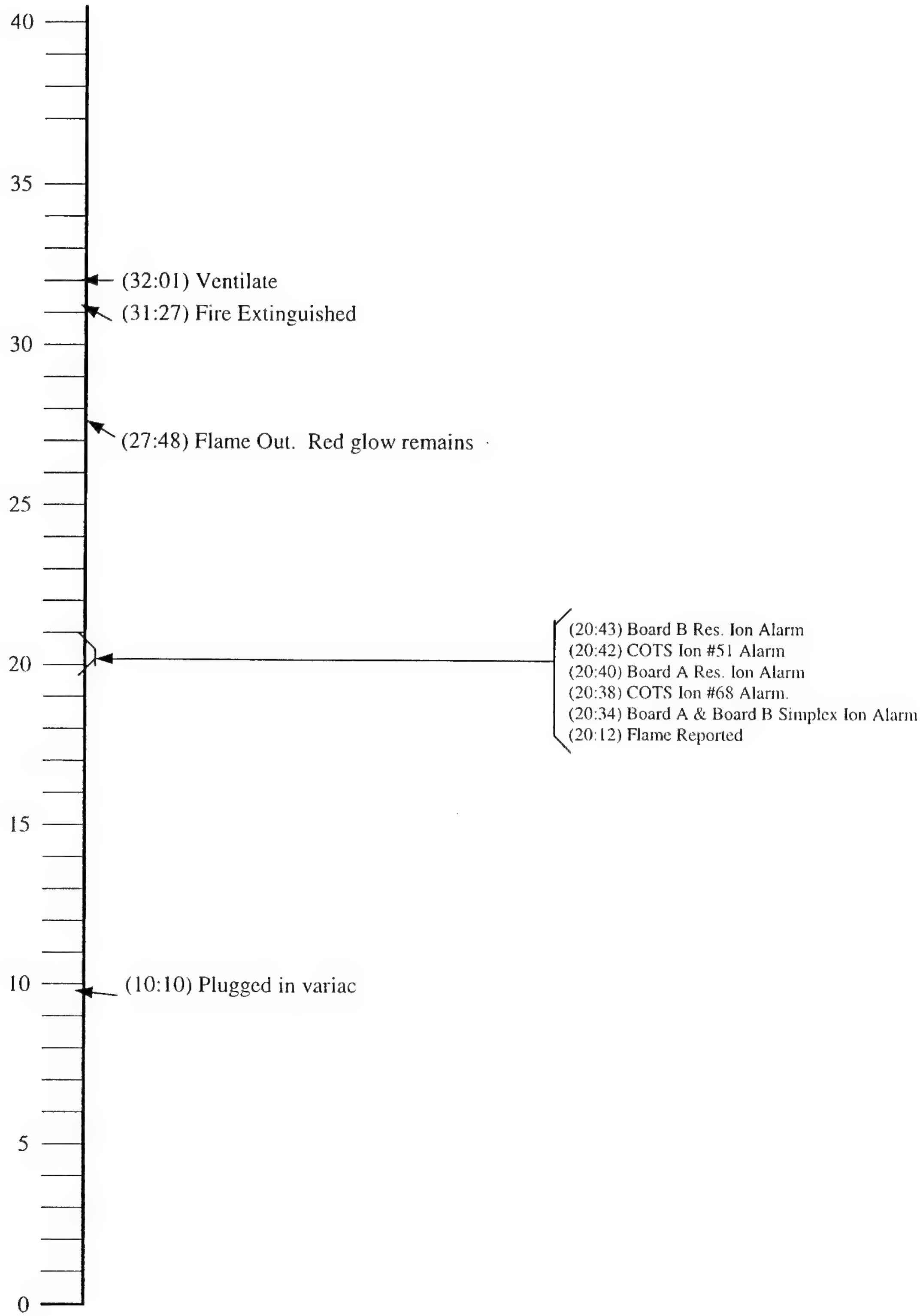

Fig. B15 – Timeline of events for Test MV-14

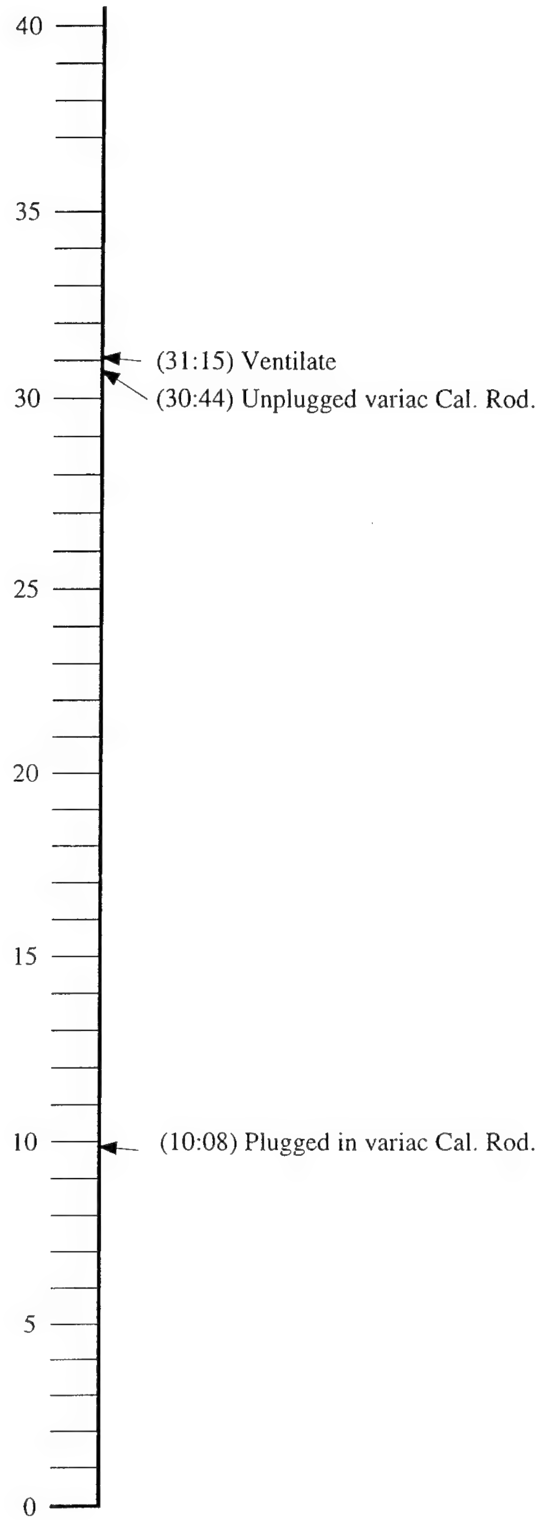

Fig. B16 – Timeline of events for Test MV-15

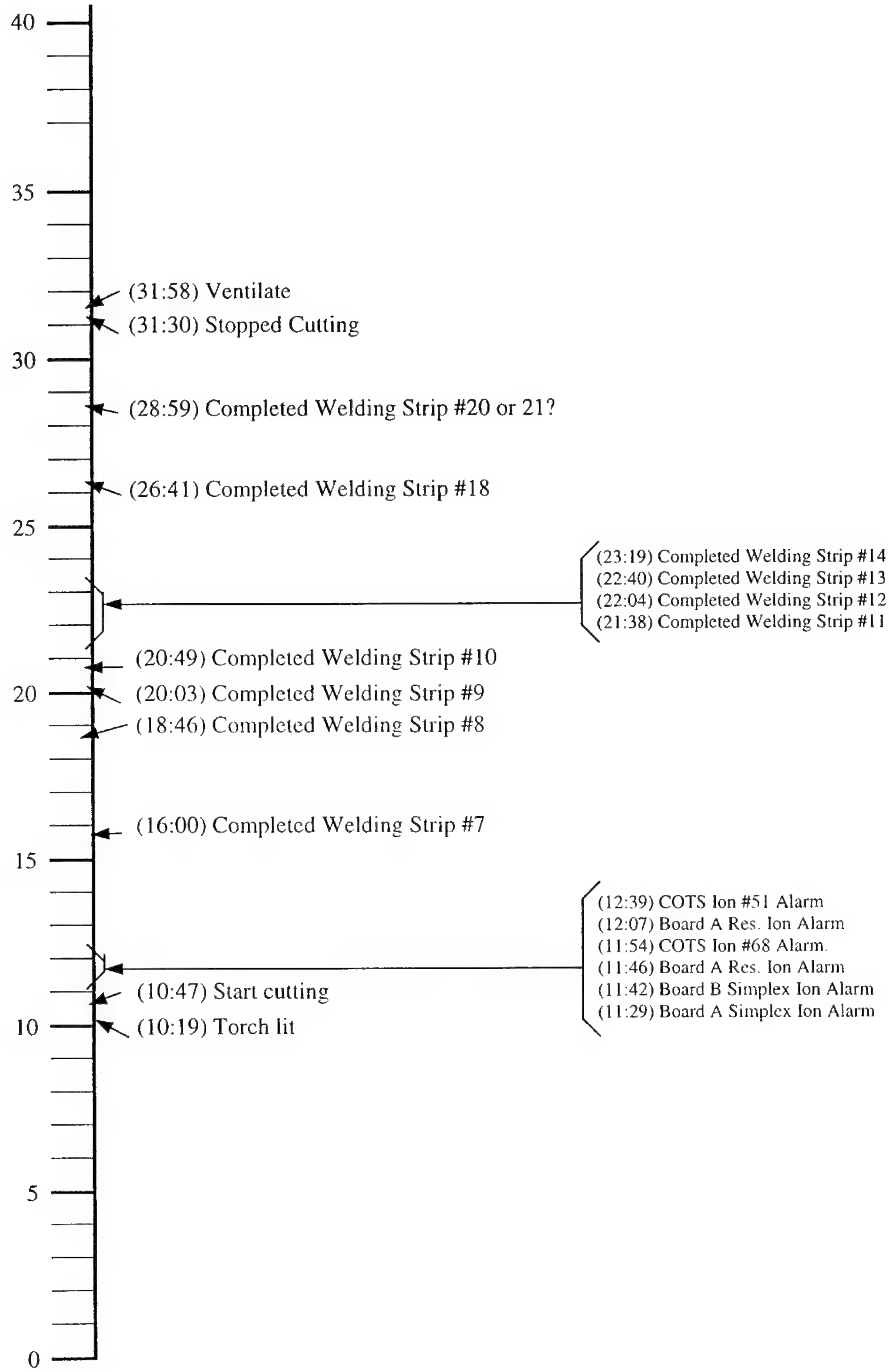

Fig. B17 – Timeline of events for Test MV-16

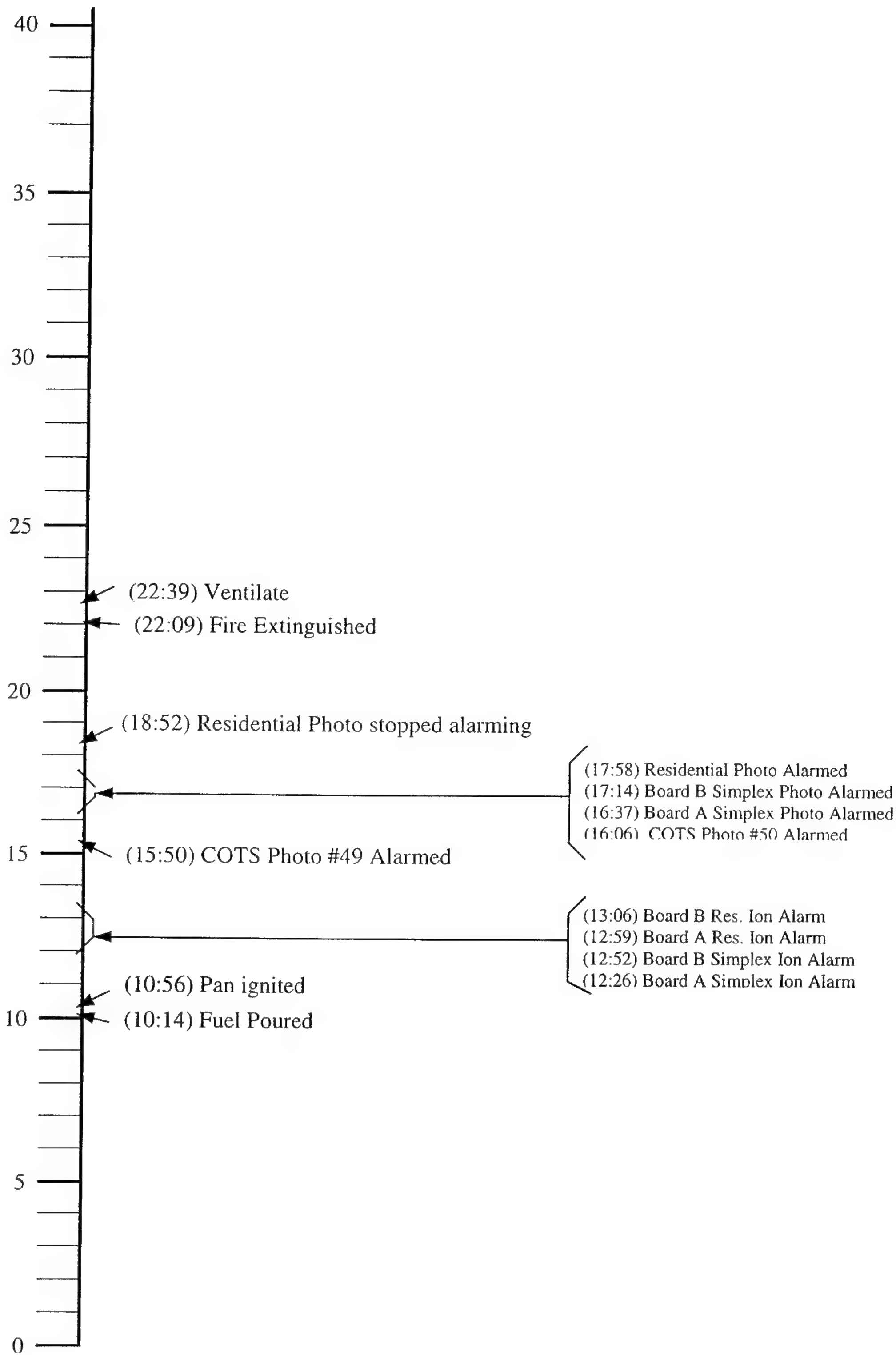

Fig. B18 – Timeline of events for Test MV-17

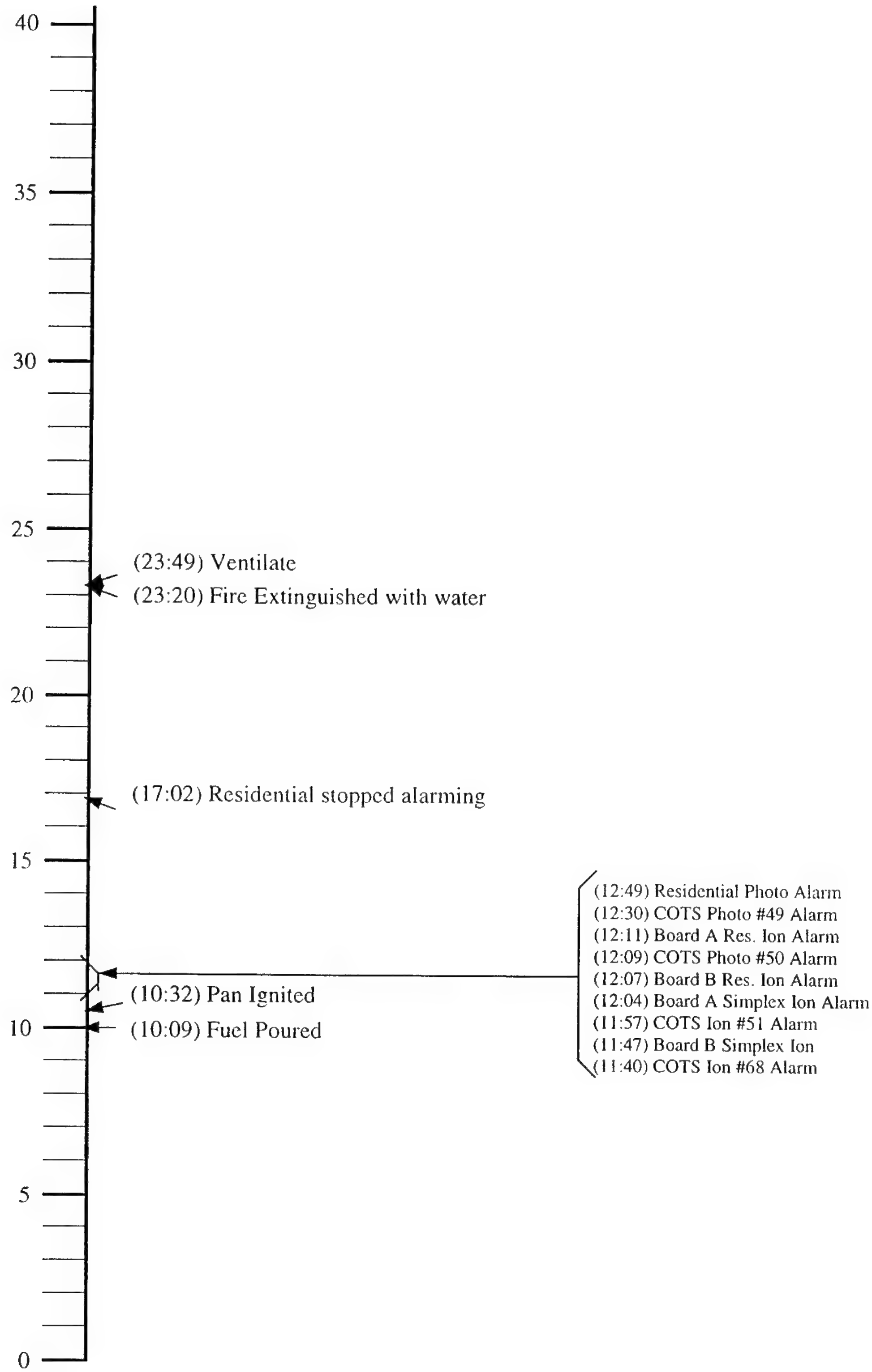

Fig. B19 – Timeline of events for Test MV-18

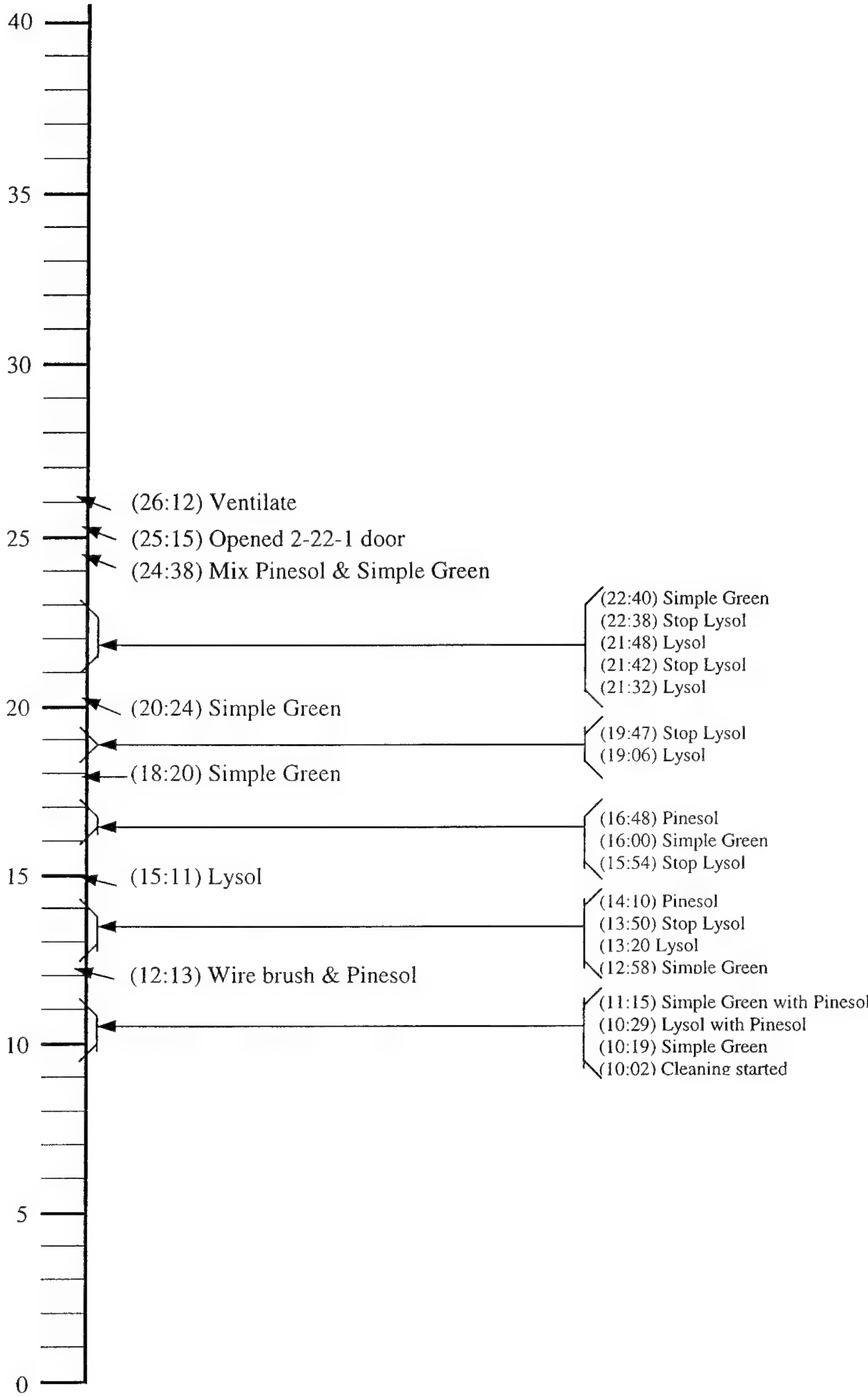

Fig. B20 – Timeline of events for Test MV-19

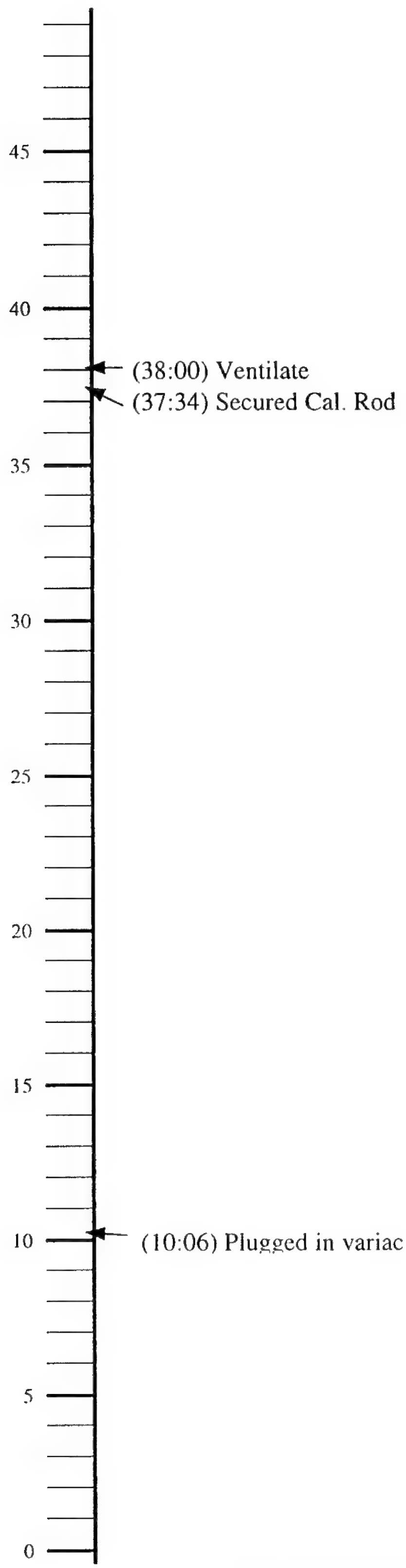

Fig. B21 – Timeline of events for Test MV-20

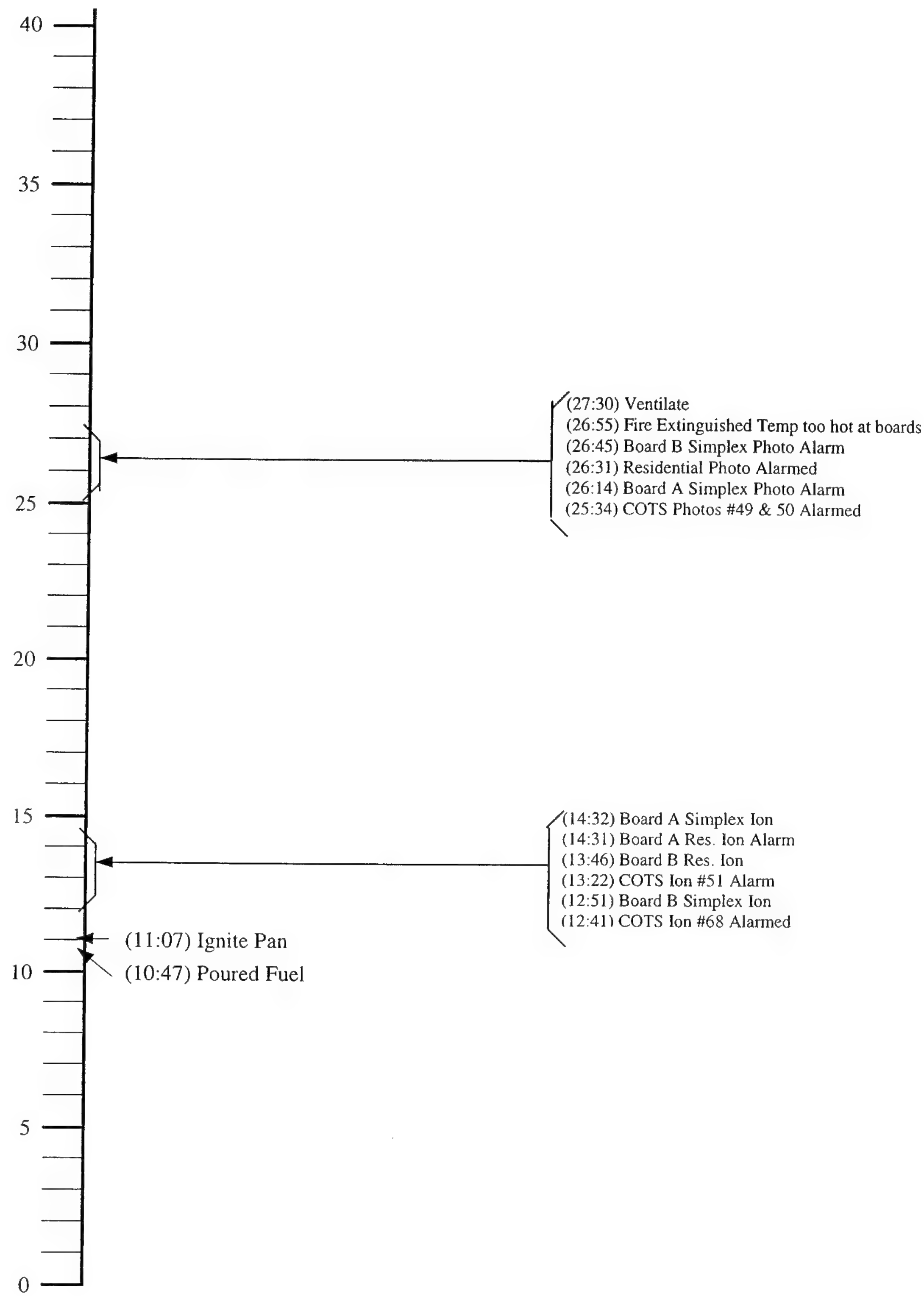

Fig. B22 – Timeline of events for Test MV-21

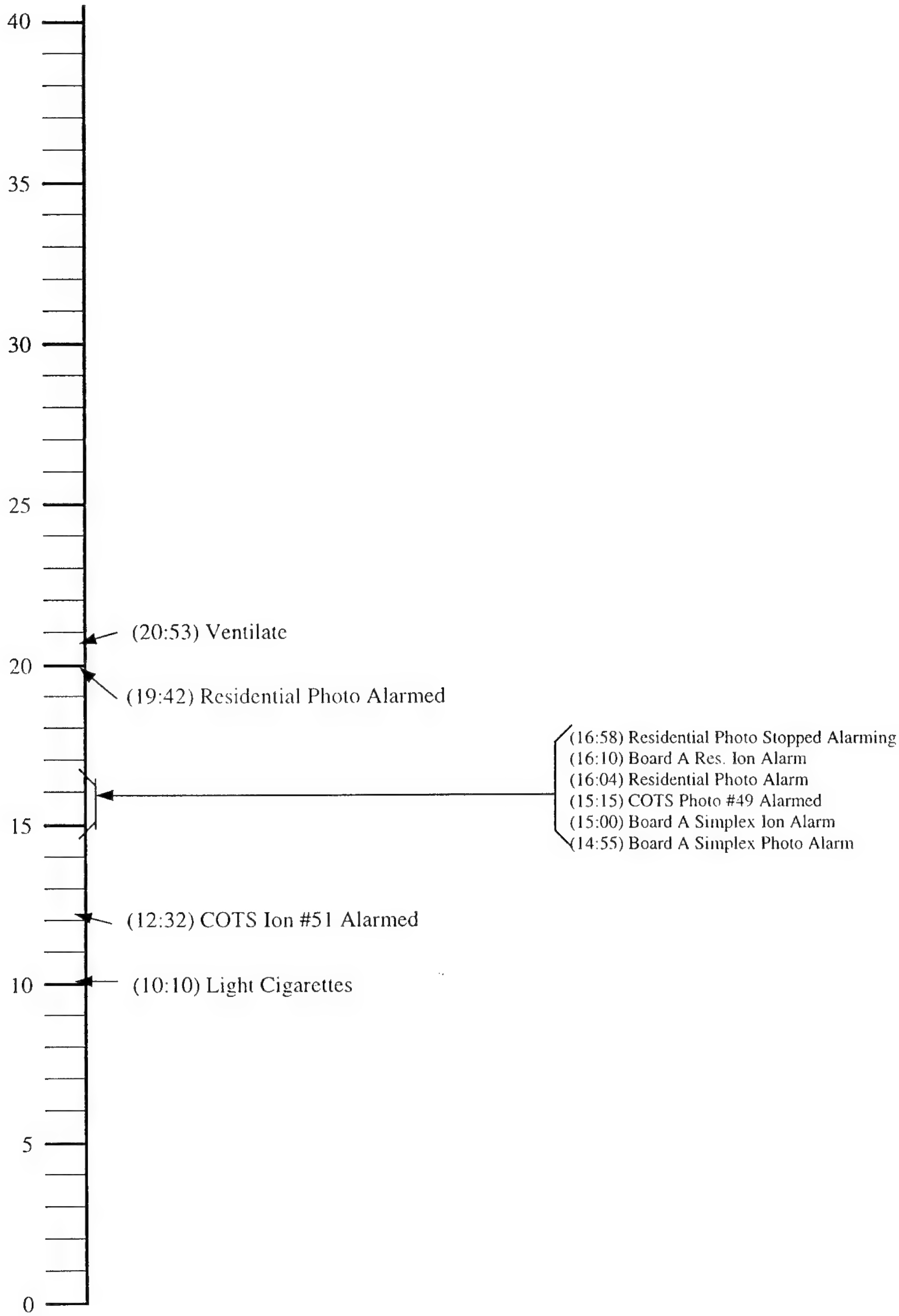

Fig. B23 – Timeline of events for Test MV-22

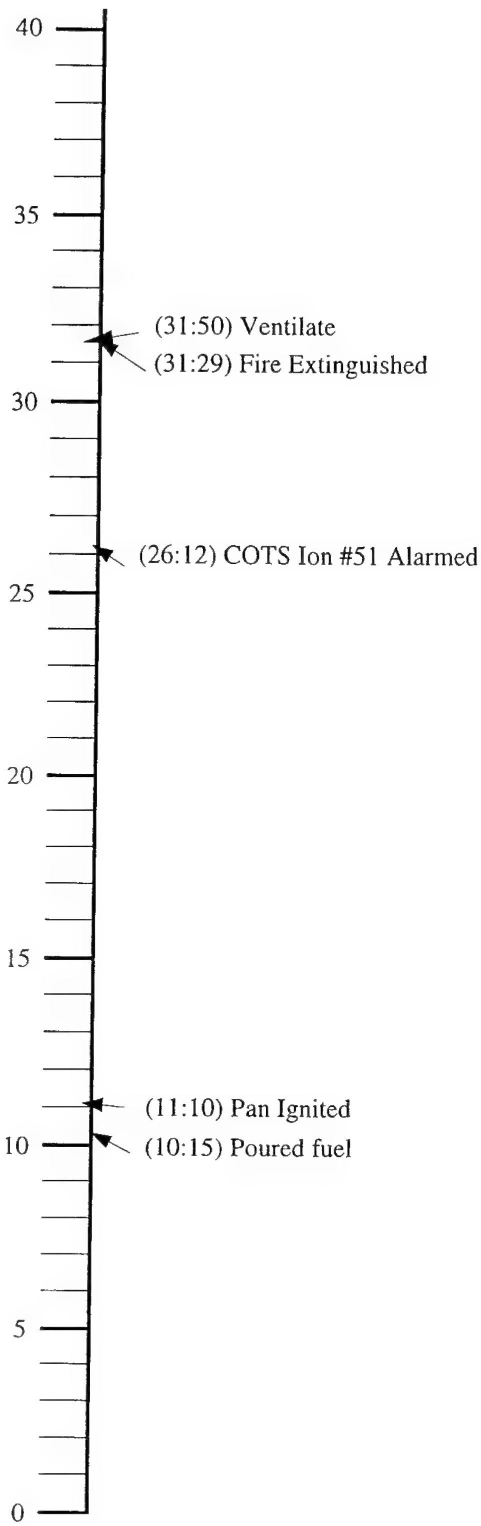

Fig. B24 – Timeline of events for Test MV-23

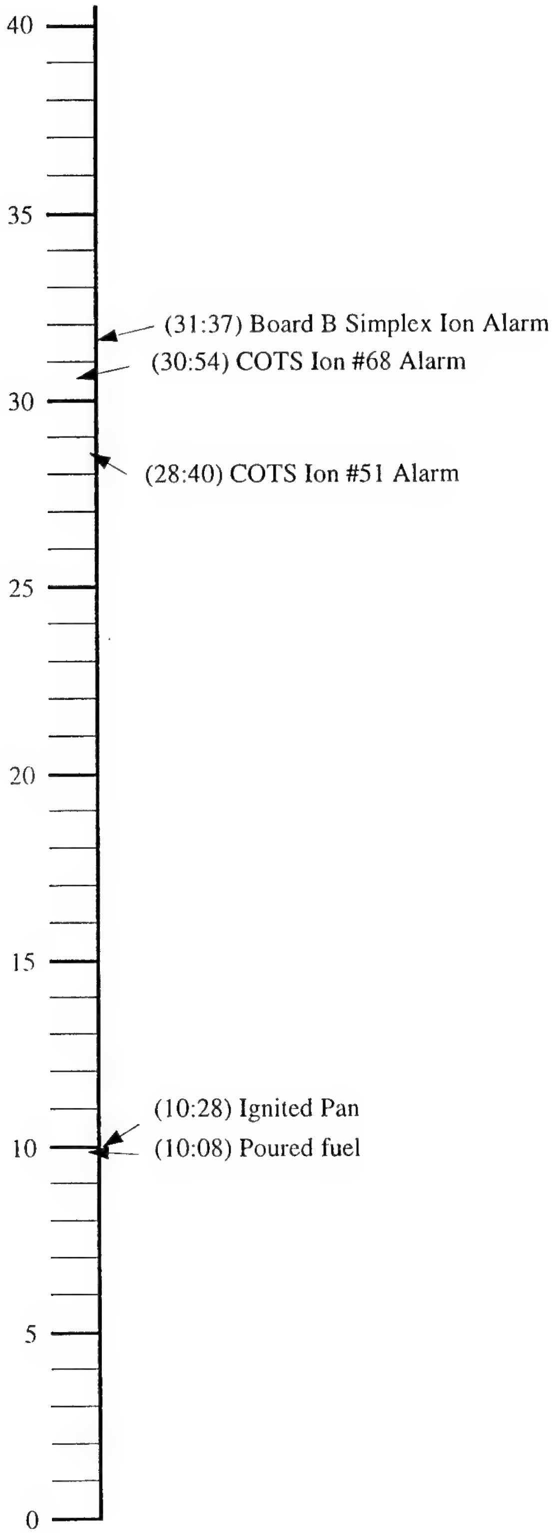

Fig. B25 – Timeline of events for Test MV-24

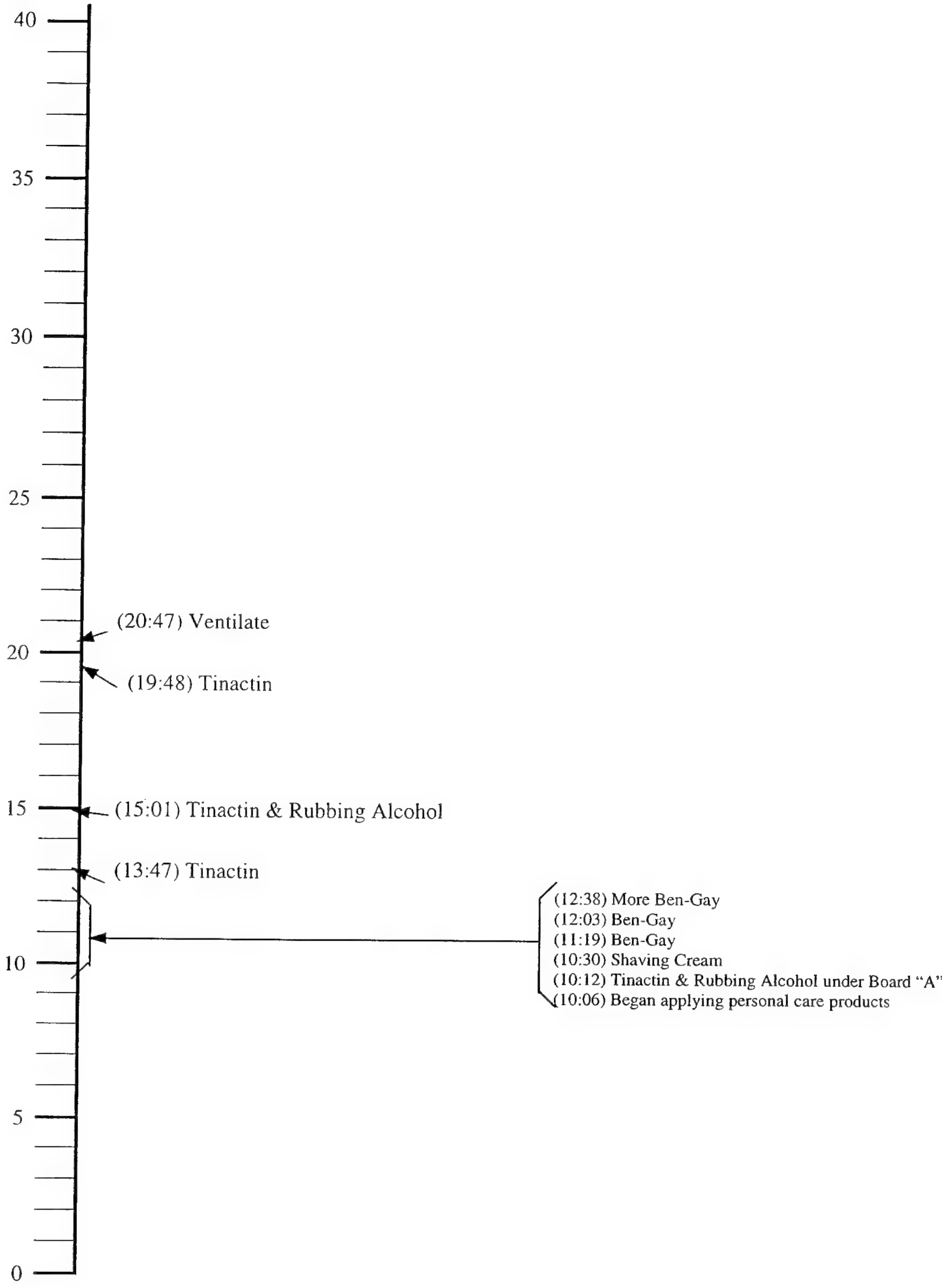

Fig. B26 – Timeline of events for Test MV-25

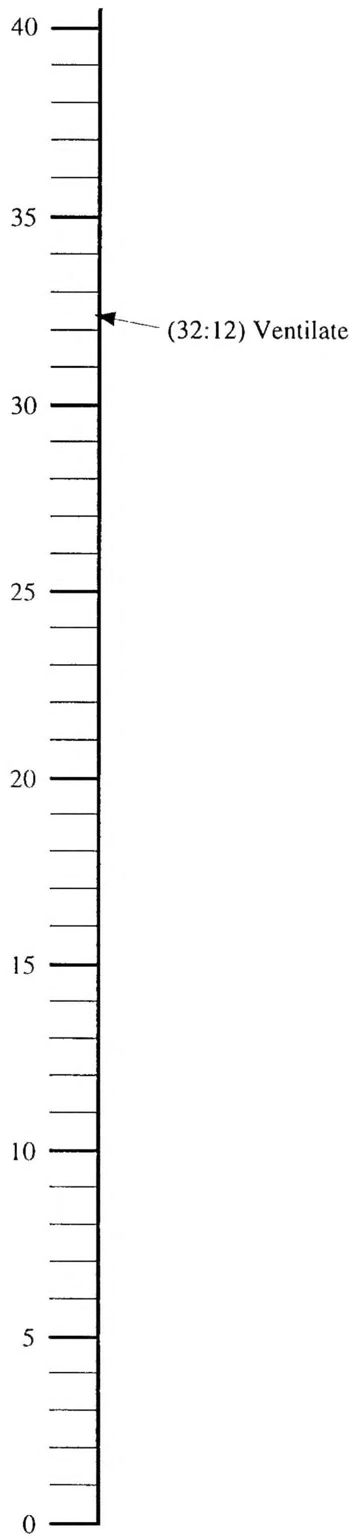

Fig. B27 – Timeline of events for Test MV-26

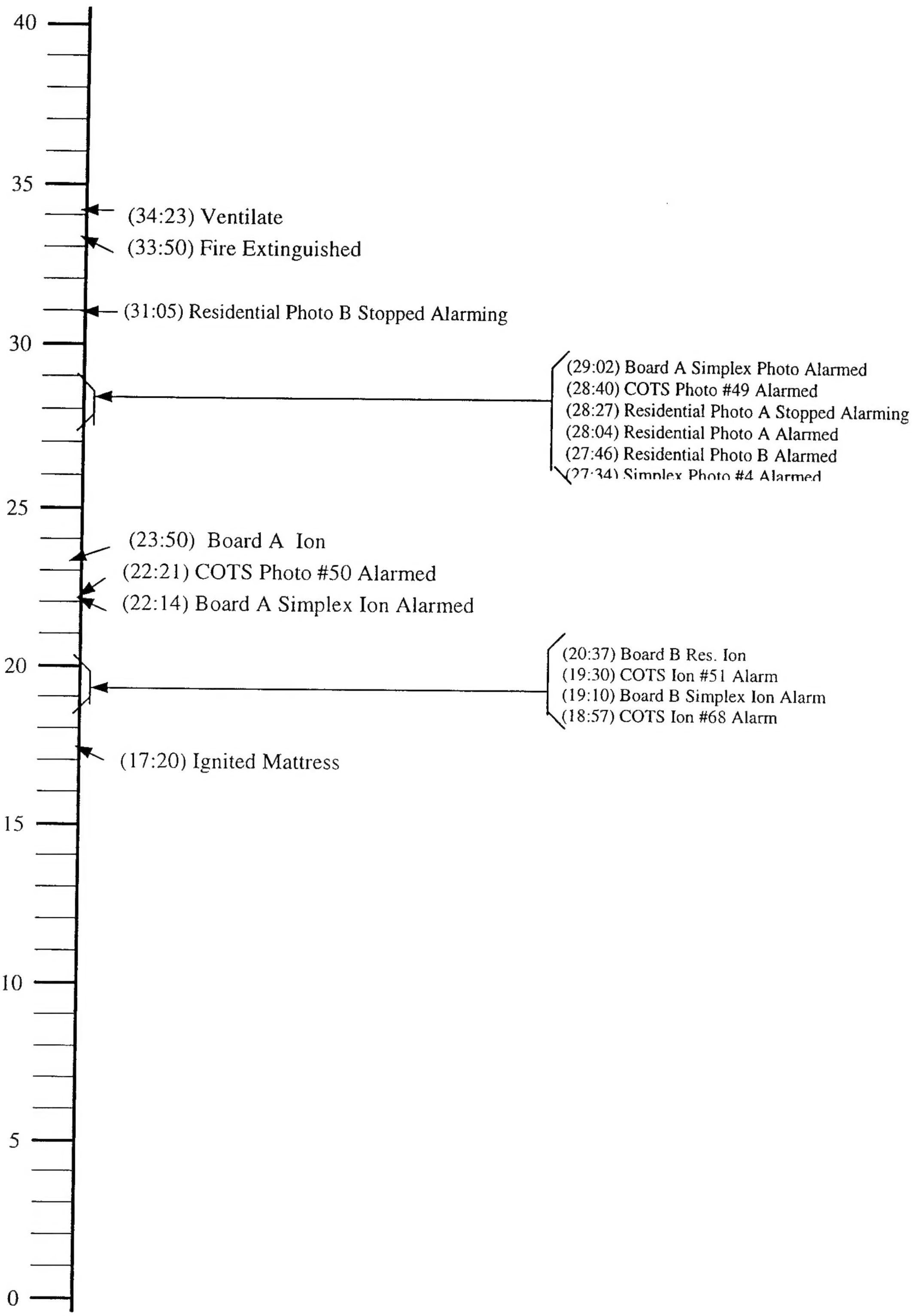

Fig. B28 – Timeline of events for Test MV-27

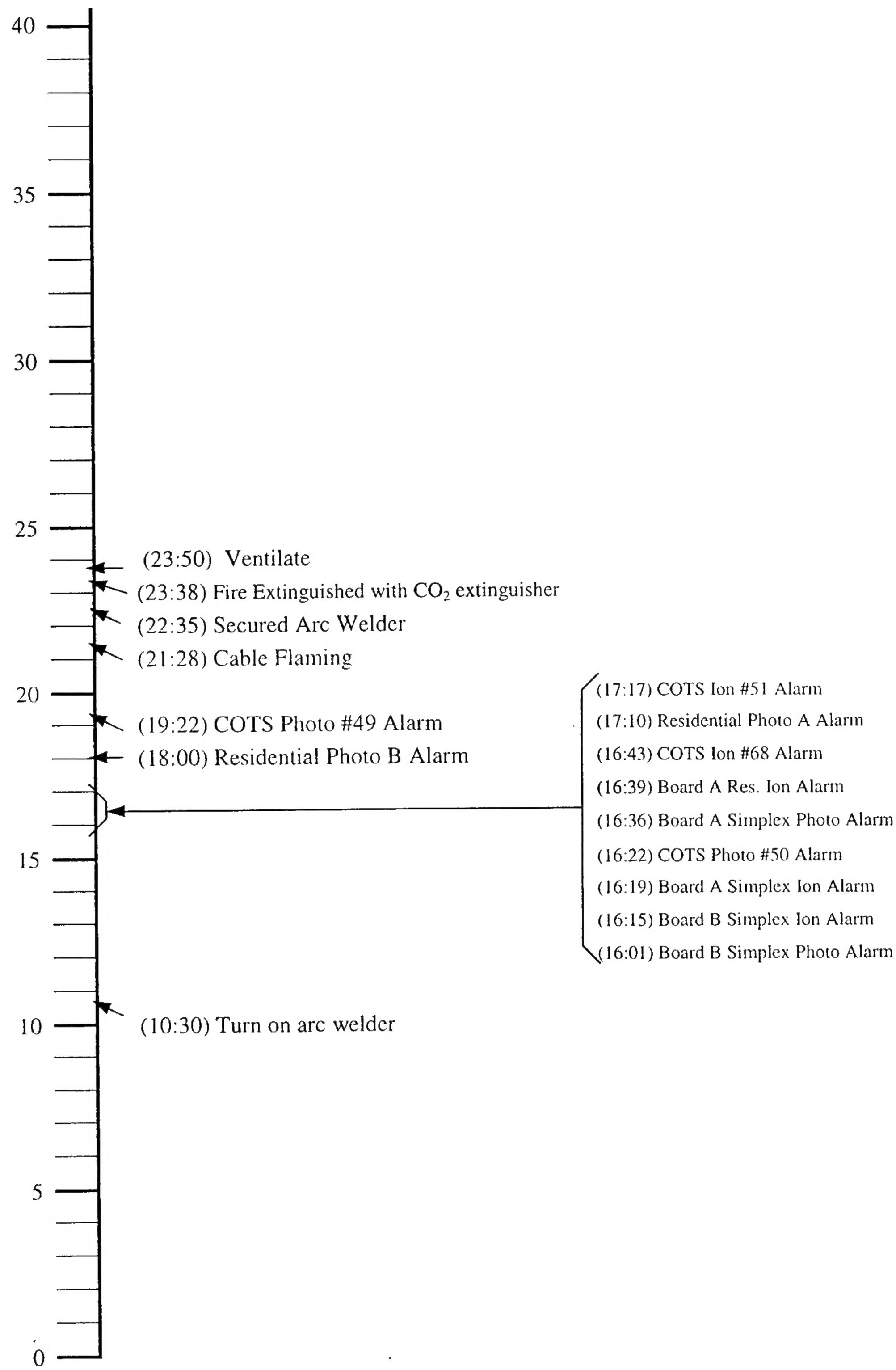

Fig. B29 – Timeline of events for Test MV-28

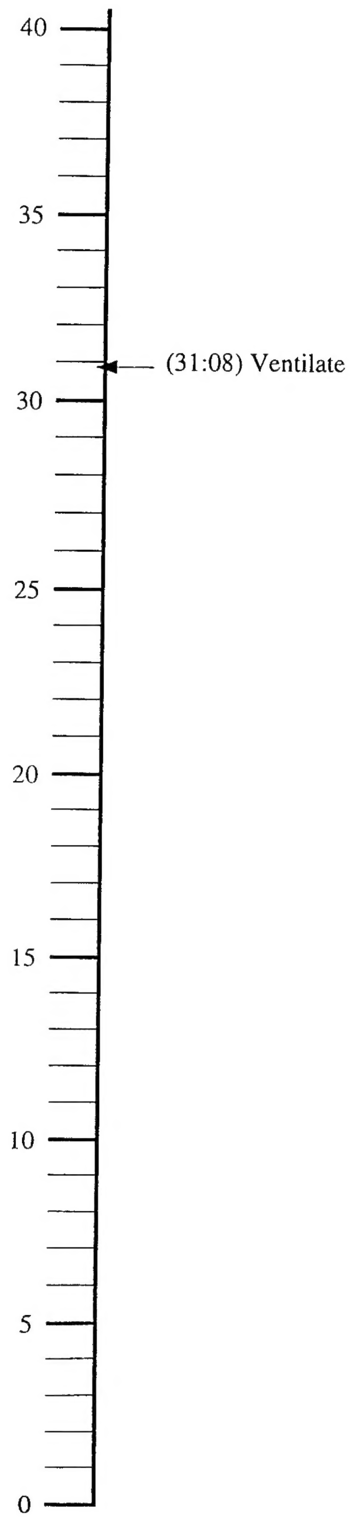

Fig. B30 – Timeline of events for Test MV-29